PB84-154269

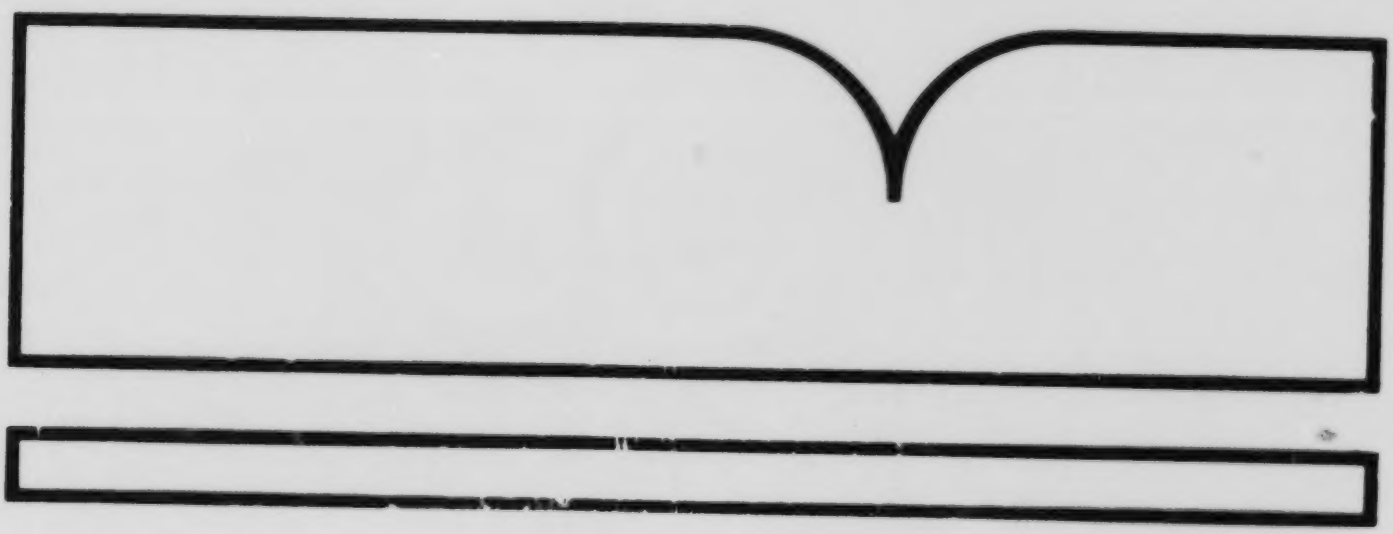
Impact of Algal-Available Phosphorus on Lake Erie Water Quality: Mathematical Modeling

Clarkson Coll. of Technology, Potsdam, NY

Prepared for

Environmental Research Lab.-Duluth, MN

Feb 84



U.S. Department of Commerce
National Technical Information Service
NTIS

PB84-154269

EPA-600/3-84-027
February 1984

IMPACT OF ALGAL-AVAILABLE PHOSPHORUS ON LAKE ERIE WATER QUALITY: Mathematical Modeling

by

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Grant No. CR 807155-03

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DULUTH, MINNESOTA 55804

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1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/3-84-027		PB84 154269

4. TITLE AND SUBTITLE	5. REPORT DATE
Impact of Algal-Available Phosphorus on Lake Erie Water Quality: Mathematical Modeling	February 1984
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
D. K. Salisbury, J. V. DePinto, and T. C. Young	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Department of Civil and Environmental Engineering Clarkson College of Technology Potsdam, New York 13676	11. CONTRACT/GRANT NO. 807155
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Duluth, Minnesota 55804	14. SPONSORING AGENCY CODE EPA-600/03

15. SUPPLEMENTARY NOTES

16. ABSTRACT

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From 1970 to 1980, 23.4% of the total external unavailable phosphorus load to Lake Erie was bioavailable. The eleven year total phosphorus load to Lake Erie contained 34.4% SRP, 15.3% EUP, and a significant 50.3% ERP. Trend analysis demonstrated that from 1970 to 1980 bioavailable phosphorus loading decreased at a slower rate than point source phosphorus loading decreased.

The significance of the phosphorus proportioning technique was ascertained using a multi-nutrient phytoplankton model with the 1970 and 1975 phosphorus loading data. The model was modified to represent the distinction between allochthonous and autochthonous unavailable phosphorus. Comparisons between the original and modified models showed that the modified phosphorus dynamics proved to be a viable alternative to the concept of settling soluble phosphorus from the water column.

Sensitivity analyses were performed and demonstrated the need for additional research to examine the in-lake dynamics of allochthonous ultimately-available phosphorus from Lake Erie tributaries. Continued research on the extent and rate of SRP release, and the settling velocity of external ultimately-available phosphorus from Lake Erie tributaries is recommended.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	87
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

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ABSTRACT

Accurate estimates of the forms and bioavailability of phosphorus loadings are necessary for loading trend analysis and water quality model development. Total phosphorus loading data for Lake Erie from 1970 to 1980 (U.S. Army Corps of Engineers, Buffalo District) were categorized into three forms, based on phosphorus bioavailability studies. The three forms were soluble reactive phosphorus (SRP) (immediately available for algal uptake), external ultimately-available phosphorus (EUP) (not immediately available but converted to an available form at a specific rate), and external refractory phosphorus (ERP) (never available for algal uptake).

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The significance of the phosphorus proportioning technique was ascertained using a multi-nutrient phytoplankton model (DiToro and Connolly 1980) with the 1970 and 1975 phosphorus loading data. The model was modified to represent the distinction between external and internal unavailable phosphorus. Comparisons between the original and modified models showed that the modified phosphorus dynamics proved to be a viable alternative to the concept of settling soluble phosphorus from the water column.

Sensitivity analyses were performed and demonstrated the need for additional research to examine the in-lake dynamics of allochthonous ultimately-available phosphorus from Lake Erie tributaries. Continued research on the extent and rate of SRP release, and the settling velocity of external ultimately-available phosphorus from Lake Erie tributaries is recommended.

This report was submitted in partial fulfillment of Grant No. CR 807155-03 by Clarkson College of Technology under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from April 15, 1982 to September 30, 1983, and work was completed as of July, 1983.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

cfs	cubic feet per second
Chl-a	Chlorophyll-a
cms	cubic meters per second
d	day
KM, km	kilometer
L	liter
LEM1	Lake Erie model with two P systems: SRP and ultimately-available P, with SRP settling
LEM2	Same as LEM1, without SRP settling
LEM3	Lake Erie model with four P systems: SRP, EUP, ERP, and IUP, without SRP settling
m/d	meters/day
mg	milligram
MI	mile
MT	metric ton
sed.	Sediments (Figure 17)
ug	microgram
USGS	United States Geological Survey
yr	year

SYMBOLS

AN	Available nitrogen, ammonia + nitrate nitrogen
BAPP	Bioavailable particulate phosphorus fraction in tributary and direct non-point particulate P loads
BAPP(t)	Cumulative available phosphorus released from the sediments (ug P/100 mg dry sediment)
C	State variable concentration, carbon, or degrees Celsius
CZ	Carnivorous zooplankton
DCDA	Dual Culture Diffusion Apparatus
E	Bulk dispersion coefficient
ERP	External refractory phosphorus
EUP	External ultimately-available phosphorus
FAP	Available-P fraction of respired phytoplankton
FA	Source-specific bioavailable fraction of TEUP
HZ	Herbivorous zooplankton
I	Average daily solar radiation at segment surface, langleys/day
Is	Saturation light intensity, langleys/day
IUP	Internal ultimately-available phosphorus
K and k	Various biochemical conversion rate coefficients
Kmg	Half saturation constant for filtering rate limitation (herbivorous zooplankton), ug Chl-a/L
KmN	Half saturation constant for nitrogen, ug N/L
Kmp	Half saturation constant for phosphorus, ug PO_4-P/L
Kmr	Half saturation constant for chlorophyll-a limita-

	tion, ug Chl-a/L
KmSi	Half saturation constant for silica, ug Si/L
Km	Half saturation constant for assimilation rate limitation (herbivorous zooplankton), ug Chl-a/L
N	Nitrogen
P	Phosphorus
PC	Phosphorus to carbon ratio
PCHL	Phosphorus to chlorophyll-a ratio
PHYTO-P	total phytoplankton phosphorus
PO_4-P	orthophosphate
PP	Particulate phosphorus
Q	Advection flow
R	Various biochemical reaction rates
r(I/Is)	Light reduction factor, no units
RSi	Reactive silica
S	Sum of sources and sinks
Si	Silica
SRP	Soluble reactive phosphorus
SV	Settling velocity of TEUP (meters/day)
T	Temperature, degrees Celsius
TCH	Total chlorophyll-a
TEUP	Total external unavailable phosphorus
TP	Total phosphorus
v	Settling velocity (meters/day)
V	Volume
W	Sum of loadings
β	Assimilation limitation factor
ε_c	Carnivorous zooplankton filtering rate
ε_h	Herbivorous zooplankton filtering rate
θ	Various Arrhenius temperature coefficients for k and K, No units
[ ]	Brackets indicate concentration, mg/L or ug/L

SUBSCRIPTS

i	Segment i
k	Segment k
ℓ	State variable
T	Total
1	Saturated phytoplankton growth: R, K, and θ
2	Endogenous respiration: R, K, and θ
3	Herbivorous zooplankton filtering: R and K
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ACKNOWLEDGMENTS

The cooperation and assistance of many persons were essential in completing this project. The U.S. EPA, Large Lakes Research Station, Grosse Ile, Michigan, furnished the DiToro and Connolly nutrient/phytoplankton model of Lake Erie and the Water Quality Analysis Simulation Program (WASP). Steven M. Yaksich and David A. Melfi, U.S. Army Corps of Engineers, Buffalo District, furnished 1970-1980 Lake Erie total and ortho- phosphorus loading estimates. Scott Martin, Clarkson College, provided process experimental data on phosphorus availability. Dominic M. DiToro and John P. Connolly, Environmental Engineering and Science Division, Manhattan College, Bronx, New York furnished advice on and input data for their nutrient/phytoplankton model of Lake Erie.

SECTION 1

INTRODUCTION

Regulation of phosphorus loading is considered to be the primary method eutrophication control for Lake Erie (Task Group III 1978, PMSTF 1980). Non-point phosphorus control or additional point source control will be necessary, in addition to current point source controls, to meet the annual phosphorus load of 11,000 metric tons recommended by the Task Group (U.S. Army Corps of Engineers, Buffalo District 1982). Knowledge of tne forms and bioavailability of all phosphorus sources is essential since implementation of the most cost-effective load control measures depend upon identification of sources carrying high bioavailable phosphorus loads.

Recent research has been undertaken at Clarkson College of Technology (DePinto et al. 1981, Young et al. 1982, Martin 1983) to improve the accuracy of estimates of the form and reactivity of phosphorus loadings to Lake Erie. Since mathematical models of the eutrophication process are used to form management strategies it is necessary to develop them to represent biochemical and physical processes as accurately as current scientific knowledge permits. It was the purpose of this study to incorporate the phosphorus bioavailability findings at Clarkson College into an existing (calibrated and verified) Lake Erie phytoplankton model (DiToro and Connolly 1980).

Recent deterministic phytoplankton models of the Great Lakes (Bierman et al. 1980, DiToro and Connolly 1980, DiToro and Matystik 1980, Rodgers and Salisbury 1981a) considered phosphorus loads and water column phosphorus from internal and external sources to exist in two forms, available and ultimately-available. Available phosphorus was considered to be soluble reactive P (SRP) and immediately available for phytoplankton uptake. Ultimately-available phosphorus, on the other hand, was considered to be particulate P (PP) or dissolved P which required a biochemical conversion before becoming available for algal uptake. No distinction was made between the reactivities of ultimately-available P produced within the water column by primary productivity (internal or autochthonous) and ultimately-available P supplied by tributaries, shore erosion, and municipal effluent discharges (external or allochthonous). The empirical rate coefficient for the conversion of ultimately-available P to

available P, utilized in water quality models, was based primarily on the conversion of autochthonous ultimately-available P. In the past, this discrepancy was unavoidable due to the lack of empirical evidence to demonstrate the difference between the release of available P from allochthonous ultimately-available PP and the conversion to available P from autochthonous ultimately-available P. However, research by DePinto et al. (1981), Young et al. (1982), and Martin (1983) has demonstrated subtle differences in these processes.

To determine the available phosphorus release rate from allochthonous ultimately-available PP, DePinto et al. (1981) performed bioassays on suspended sediments from Lake Erie tributaries. In addition, Young et al. (1982) performed bioassays on wastewater from municipal treatment plants on the lower Great Lakes. Both research findings indicated a rapid release rate from allochthonous ultimately-available PP relative to the rate of conversion of autochthonous ultimately-available P. The scope of the modeling effort reported here was to examine the usefulness of differentiating between allochthonous and autochthonous ultimately-available P forms with respect to predictions on in-lake phosphorus and algal dynamics by incorporating findings of DePinto et al. 1981, Young et al. 1982, and Martin 1983 into a modified version of an existing Lake Erie phytoplankton model (DiToro and Connolly 1980).

The model refinement involved the addition of two new forms of phosphorus, total external unavailable P (TEUP) and external refractory P (ERP), to the model framework. TEUP was the sum of ERP and the external ultimately-available P (EUP). Both EUP and ERP were sediment-bound particulate phosphorus which entered the lake via direct or indirect (tributary) sources. EUP, not immediately available for algal uptake, was converted to bioavailable P. ERP, in contrast, did not contribute to the available P pool while the sediments were in the water column. The model description and refinement are discussed in Section 5.

In order to evaluate the effect of the model refinement, comparisons were made between simulations of soluble reactive P, total P, and total chlorophyll-a by three Lake Erie models. Two of the models, LEM1 and LEM2, had two P forms, SRP and unavailable P. To effect a reasonable calibration, DiToro and Connolly found it necessary to settle from the water column the dissolved P form, SRP. The DiToro and Connolly model was examined with SRP settling (LEM1) and without SRP settling (LEM2). The model reported here, LEM3, had four phosphorus forms, SRP, EUP, ERP, and autochthonous unavailable P. LEM3 assumed that SRP does not settle from the water column. The model simulations are compared in Section 6.

All three models utilized the same total phosphorus loading data (D.A. Melfi, U.S. Army Corps of Engineers, Buffalo District, personal communication, 1982). For LEM1 and LEM2, the total phosphorus load was divided into SRP and unavailable P. For LEM3, which also received SRP loading, the unavailable P load was repartitioned into EUP and ERP loads based on research by DePinto et al. 1981, Young et al. 1982, and Martin 1983. The phosphorus loading data used in this comparison were not identical to those used by DiToro and Connolly to calibrate their model. The U.S. Army Corps of Engineers, Buffalo district revised their estimates of total phosphorus and orthophosphate loadings to Lake Erie subsequent to the DiToro and Connolly modeling effort. None of the models was recalibrated to the revised phosphorus loading data so as to objectively compare only the effect of the differences in the three phosphorus dynamics approaches. The phospnorus loading data compilation and analysis for LEM3 is described in Section 4.

To further evaluate the usefulness of LEM3 sensitivity analyses were performed. Three empirical parameters determined by the research efforts of DePinto et al. (1981), Kwolek (1982), Young et al. (1982), and Martin (1983) were varied. The sensitivity of LEM3 to changes in the bioavailable fraction of TEUP in tributary and direct non-point P sources, the rate of SRP release from allochthonous ultimately-available PP, and the settling velocity of TEUP were examined. LEM3 responses were evaluated relative to SRP, TP, and total chlorophyll-a concentrations in the water column. The sensitivity analyses are presented in Section 7.

SECTION 2

CONCLUSIONS

1. Fractionation of Lake Erie phosphorus loading data from 1970 to 1980 into soluble reactive P (SRP), external ultimately-available P (EUP), and external refractory P (ERP) revealed that, on average, only 49.7% of the total P load was bioavailable (34.3% SRP + 15.3% EUP). Also during this period, only 23.4% of the total particulate P loading was ultimately-bioavailable (EUP).

2. From 1970 to 1980, the rate of decrease in the bioavailable P loading to Lake Erie was slower than the rate of decrease in the total P loading from point sources. This type of response is to be expected when there is less than a one-to-one correspondence between percent total P load reduction and bioavailable P load reduction. Control measures aimed at non-point sources would probably exacerbate this problem.

3. The simulations of SRP, TP, and chlorophyll-a by our uncalibrated LEM3, which did not settle SRP, compared quite favorably with the simulations of the calibrated DiToro and Connolly model (LEM1), which included water column SRP settling. The LEM3 simulations were superior to those of LEM2 (DiToro model without SRP settling).

4. The proposed refinement (LEM3) of the phosphorus dynamics in the DiToro and Connolly Lake Erie model better reflects in-lake responses to various P management strategies and offers a mechanistic explanation of the in-lake phosphorus observations and a plausible alternative to the concept of SRP settling from the water column.

5. Apparent overprediction by LEM3 of spring SRP concentrations in the Western Basin could have been the result of the absence of variable phytoplankton stoichiometry in the model framework or of the omission of an SRP-dependent rate reduction factor for the conversion kinetics of external ultimately-available P (EUP) to immediately available P (SRP).

6. Of the three new parameters tested for model sensitivity, LEM3 simulations were, in general, most sensitive to BAPP fractions (the ultimately bioavailable fraction of total external unavailable P). However, water column total P concentrations responded more sensitively to variations in the total external unavailable P (TEUP) settling velocity.

SECTION 3

RECOMMENDATIONS

1. Monitoring of the bioavailable particulate phosphorus (BAPP) loading to Lake Erie will be necessary to improve the cost-effectiveness of phosphorus management strategies. BAPP load monitoring in the Detroit River is especially important.

2. Laboratory experimentation to determine the external ultimately-available phosphorus to soluble reactive phosphorus (SRP) conversion rate as a function of water-column SRP concentration and to estimate the total external unavailable phosphorus settling rate is essential for increasing scientific knowledge of the bioavailability of phosphorus in lakes. This experimentation will also facilitate further refinement of nutrient/phytoplankton models in general.

3. Observations of Lake Erie water column concentrations of the phosphorus fractions, soluble reactive phosphorus, internal ultimately-available phosphorus, external ultimately-available phosphorus and external refractory phosphorus, represented in the water quality model reported here, LEM3, are necessary to calibrate and verify LEM3.

4. Multi-year simulations with LEM3 should be performed to further test the stability of LEM3 and to ascertain the utility of LEM3 as a predictive phosphorus management tool.

SECTION 4

PHOSPHORUS LOADING DATA COMPILATION

METHODOLOGY

Total phosphorus (TP) and orthophosphate loading data were estimated (D.A. Melfi, U.S. Army Corps of Engineers, Buffalo District, personal communication, 1982) for each of the 80 sub-watersheds to Lake Erie on a monthly basis for the period 1970-1980. The P loading data were divided, by the Corps, into loads for point and non-point sources and further divided into loads originating upstream and downstream from the USGS sampling station closest to the mouth of the tributary. The methods used by the Corps to calculate TP and orthophosphate loadings to Lake Erie were detailed in Yaksich et al. (1982). For the purpose of assigning available P characteristics to the sources within the Lake Erie drainage basin, phosphorus entering tributaries downstream from the gaging station were considered to be direct P sources and phosphorus entering upstream from the gaging station were considered to be indirect P sources (Figure 1).

For use in LEM3, phosphorus loads were categorized into three forms, shown in Figure 2, based on phosphorus bioavailability studies. The three forms were soluble reactive phosphorus (SRP), external ultimately-available phosphorus (EUP), and external refractory phosphorus (ERP). SRP is immediately available for algal uptake, EUP is not immediately available but is biochemically converted to an available form at a source-specific rate, and ERP is never available for algal uptake while in the water column.

TP and orthophosphate (or SRP) loading estimations, by the Corps, allowed calculation of the particulate phosphorus (PP) load:

$$PP = TP - SRP \qquad (1)$$

The resulting PP, or total external unavailable PP, loading data were categorized into EUP and ERP, based on municipal wastewater effluent bioassays (Young et al. 1982), Lake Erie tributary suspended sediment bioassays (DePinto et al. 1981), and a Detroit River chemical extraction (Martin 1983). Municipal wastewater bioassays reflected the charac-

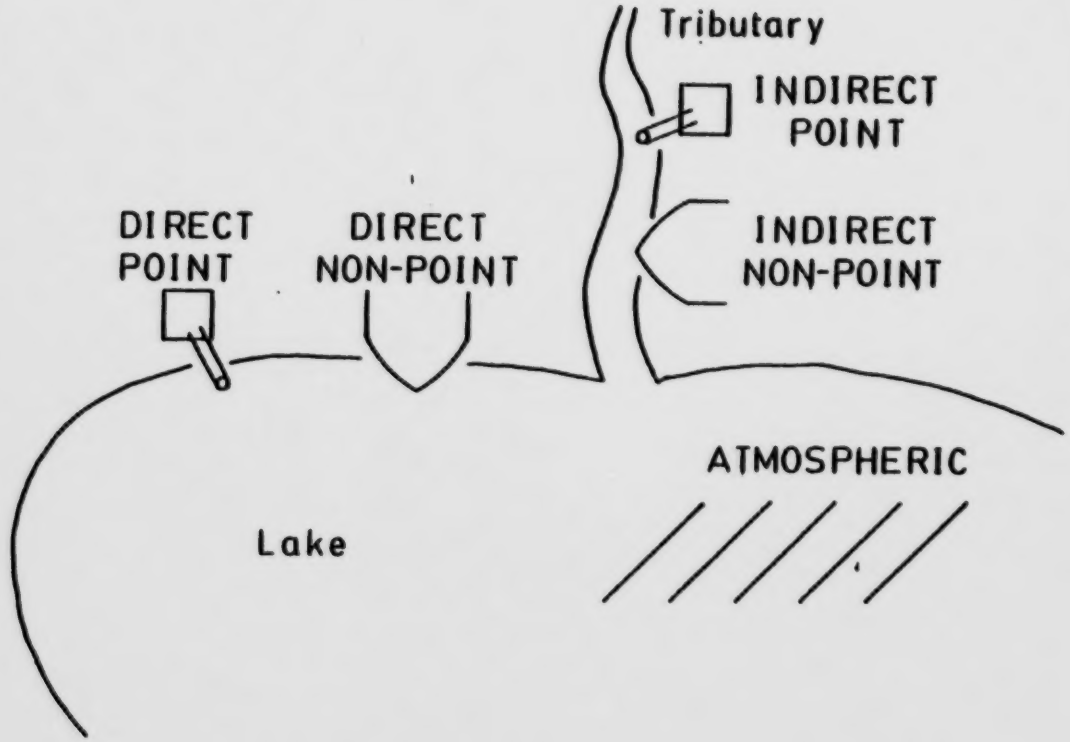

Figure 1. Source categorization of phosphorus loading to Lake Erie.

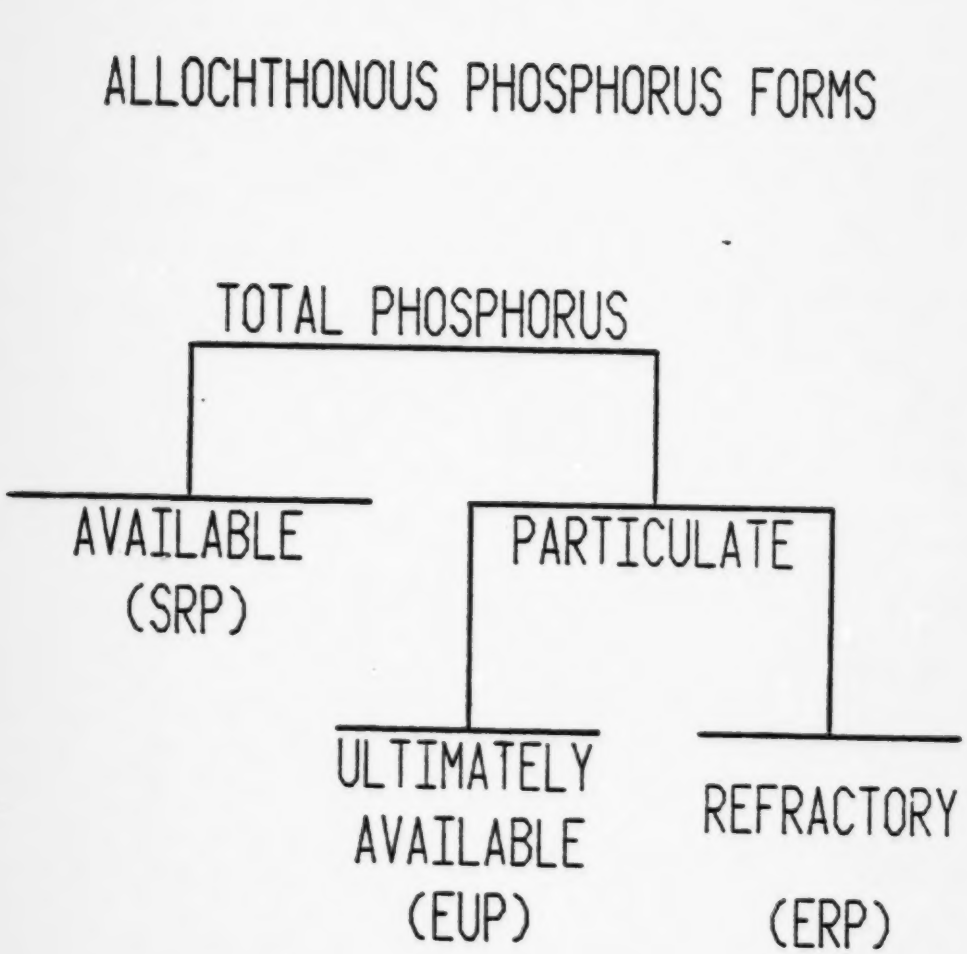

Figure 2. Fractionation of phosphorus forms in suspended sediments from tributaries.

teristics of direct point loads. Tributary suspended sediment bioassays represented indirect point and indirect non-point loads. Direct non-point loads were included with the indirect loads for this study. Although the bioavailability of direct non-point particulate P is not well known, the bioavailability is undoubtably low (Armstrong et al. 1979). The Detroit River/St. Clair Basin characteristics were based on a chemical fractionation of the P in a single composited suspended sediment sample from the Detroit River. Phosphorus availability for this sample was based on bioassay-chemical fractionation correlations (Martin 1983).

Results of municipal wastewater effluent bioassays showed that approximately 63% of the direct point particulate phosphorus load was ultimately-available for algal uptake (EUP) in all three Lake Erie Basins (Young et al. 1982). Results of bioassays on Lake Erie tributaries indicated that approximately 25%, 28%, and 8% of the indirect point and non-point PP loads were ultimately-available for algal uptake (EUP) in the Western, Central, and Eastern Basins of Lake Erie, respectively (DePinto et al. 1981). The Detroit River suspended sediment result showed that approximately 20% of the Detroit River sediment P was ultimately-available for algal uptake (EUP) (Martin 1983). Based on these fractionations, monthly calculations of EUP and ERP were performed individually for the Western, Central, and Eastern Basins.

The tributary phosphorus bioavailability results (DePinto et al. 1981, Martin 1983) were based on suspended sediment samples collected in 1980 and 1981. For the purposes of this study, these results were assumed to be representative of conditions from 1970 to 1980.

PRESENTATION

Modified phosphorus loading data for each of the three basins of Lake Erie are shown in Figures 3-8. Atmospheric and shoreline erosion P loadings are not included. The Western Basin load was the sum of the Detroit River/St. Clair Basin load, Western Basin tributary loads, and Western Basin direct point sources. The Central Basin load was the sum of Central Basin tributary loads and Central Basin direct point sources. The Eastern Basin load was the sum of Eastern Basin tributary loads and Eastern Basin direct point sources. The dominant form of phosphorus loading to Lake Erie from 1970 to 1980 was ERP. In addition, the ERP load was much more variable seasonally in all three basins than the bioavailable load (SRP + EUP). Monthly SRP, EUP, and ERP loadings for 1970-1980 for each basin of Lake Erie are included in tabular form in Appendix A.

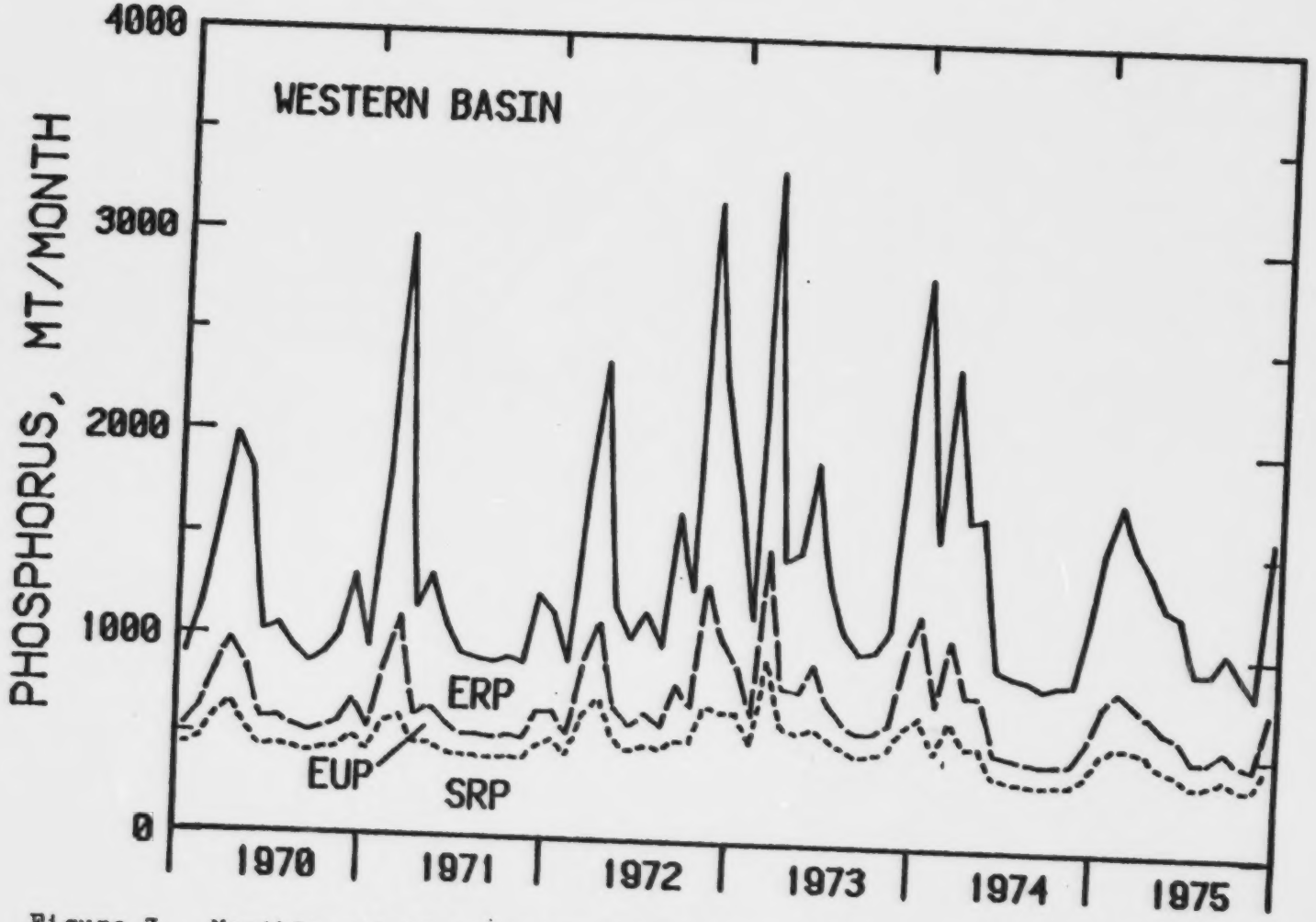

Figure 3. Monthly soluble reactive phosphorus (SRP), external ultimately-available phosphorus (EUP), external refractory phosphorus (ERP), and resultant total phosphorus loadings to the Western Basin of Lake Erie, 1970-1975.

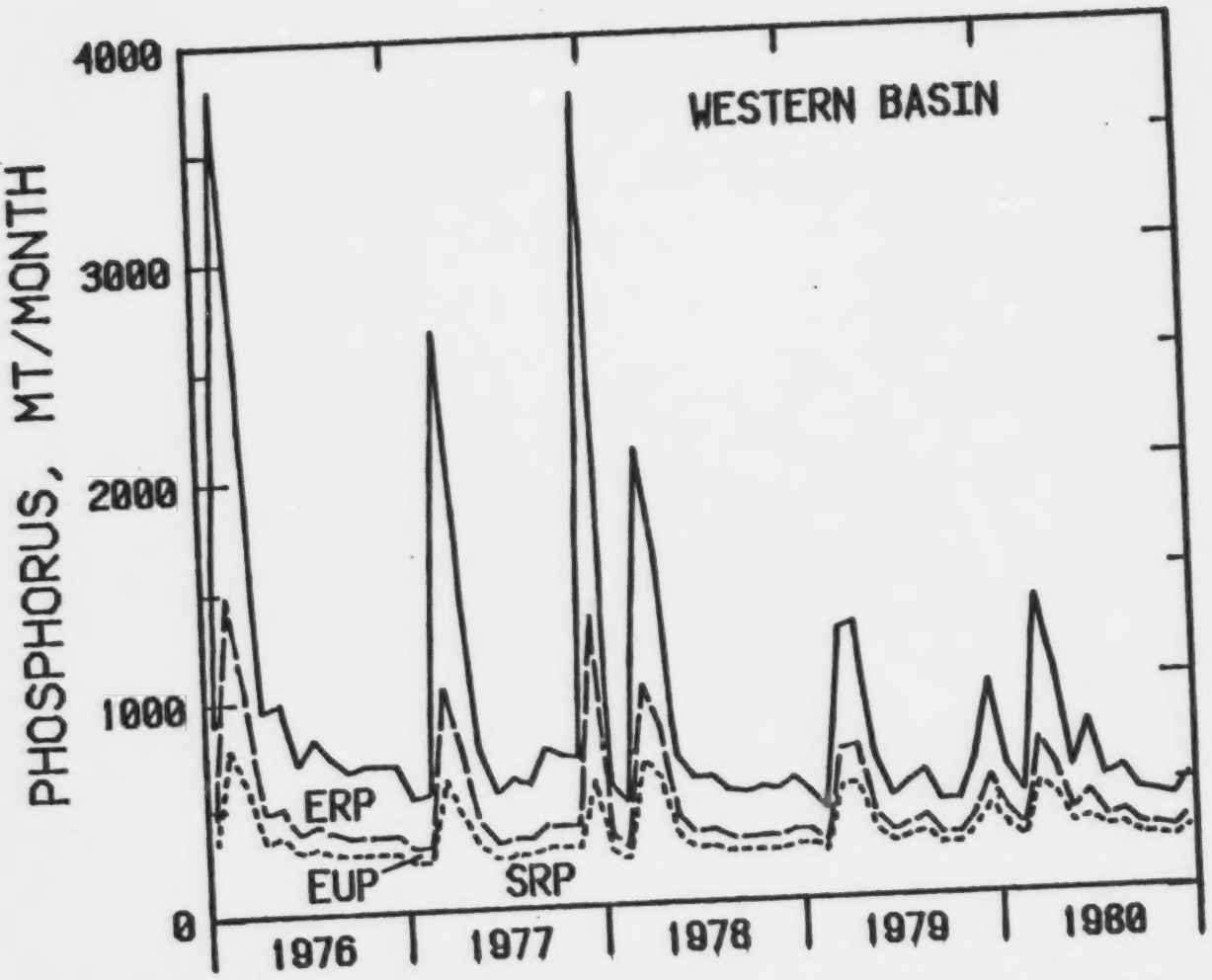

Figure 4. Monthly soluble reactive phosphorus (SRP), external ultimately-available phosphorus (EUP), external refractory phosphorus (ERP), and resultant total phosphorus loadings to the Western Basin of Lake Erie, 1976-1980.

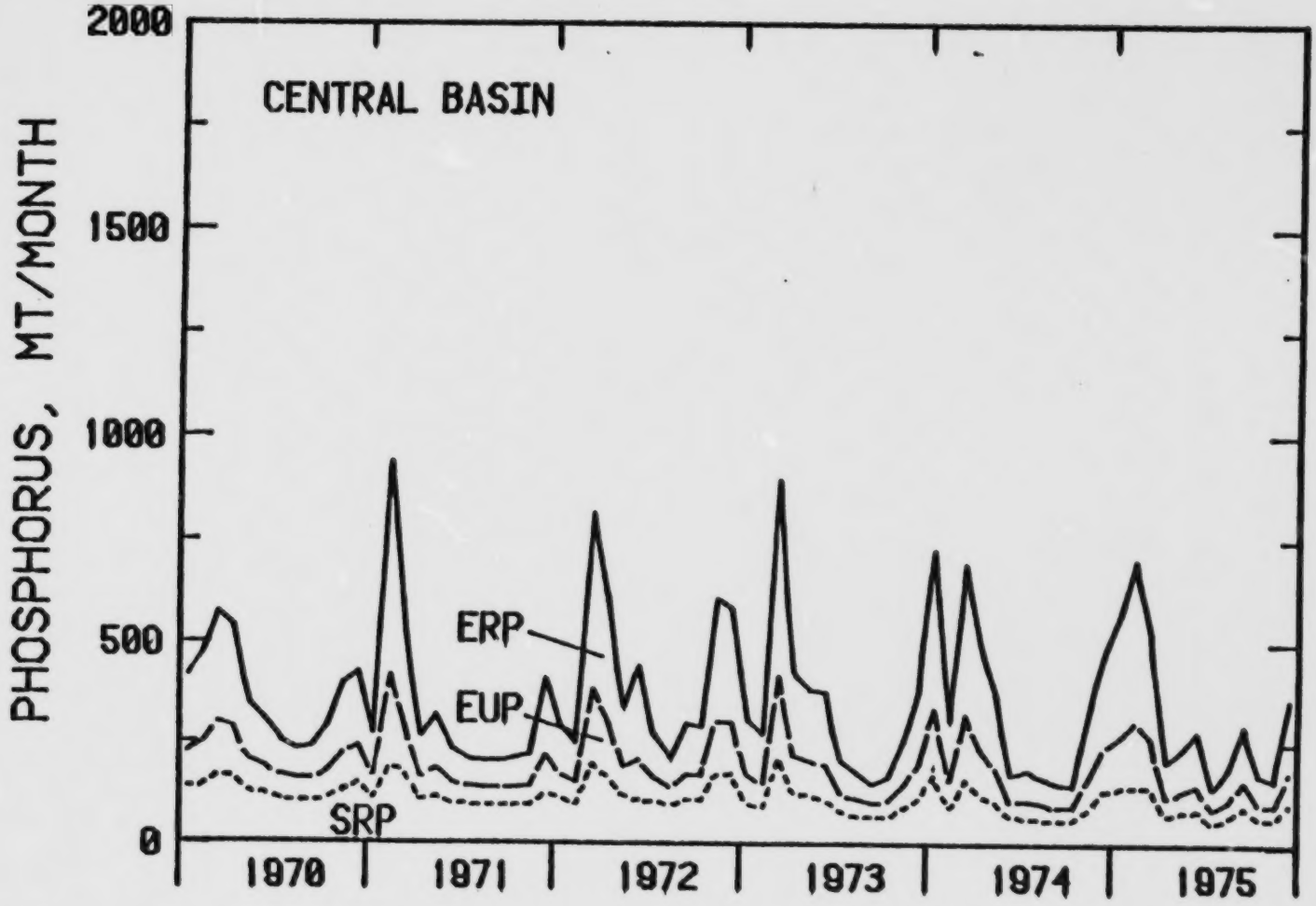

Figure 5. Monthly soluble reactive phosphorus (SRP), external ultimately-available phosphorus (EUP), external refractory phosphorus (ERP), and resultant total phosphorus loadings to the Central Basin of Lake Erie, 1970-1975.

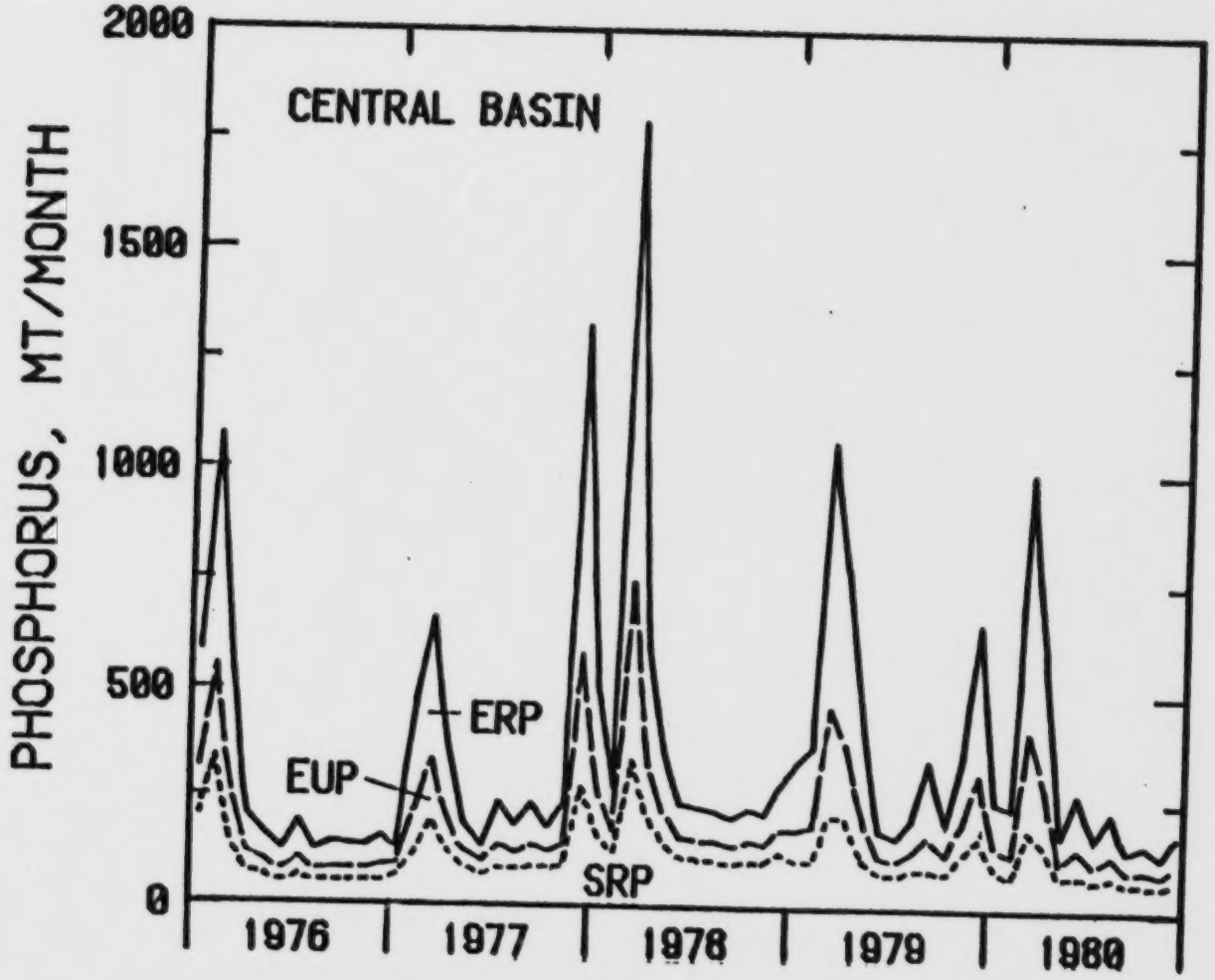

Figure 6. Monthly soluble reactive phosphorus (SRP), external ultimately-available phosphorus (EUP), external refractory phosphorus (ERP), and resultant total phosphorus loadings to the Central Basin of Lake Erie, 1976-1980.

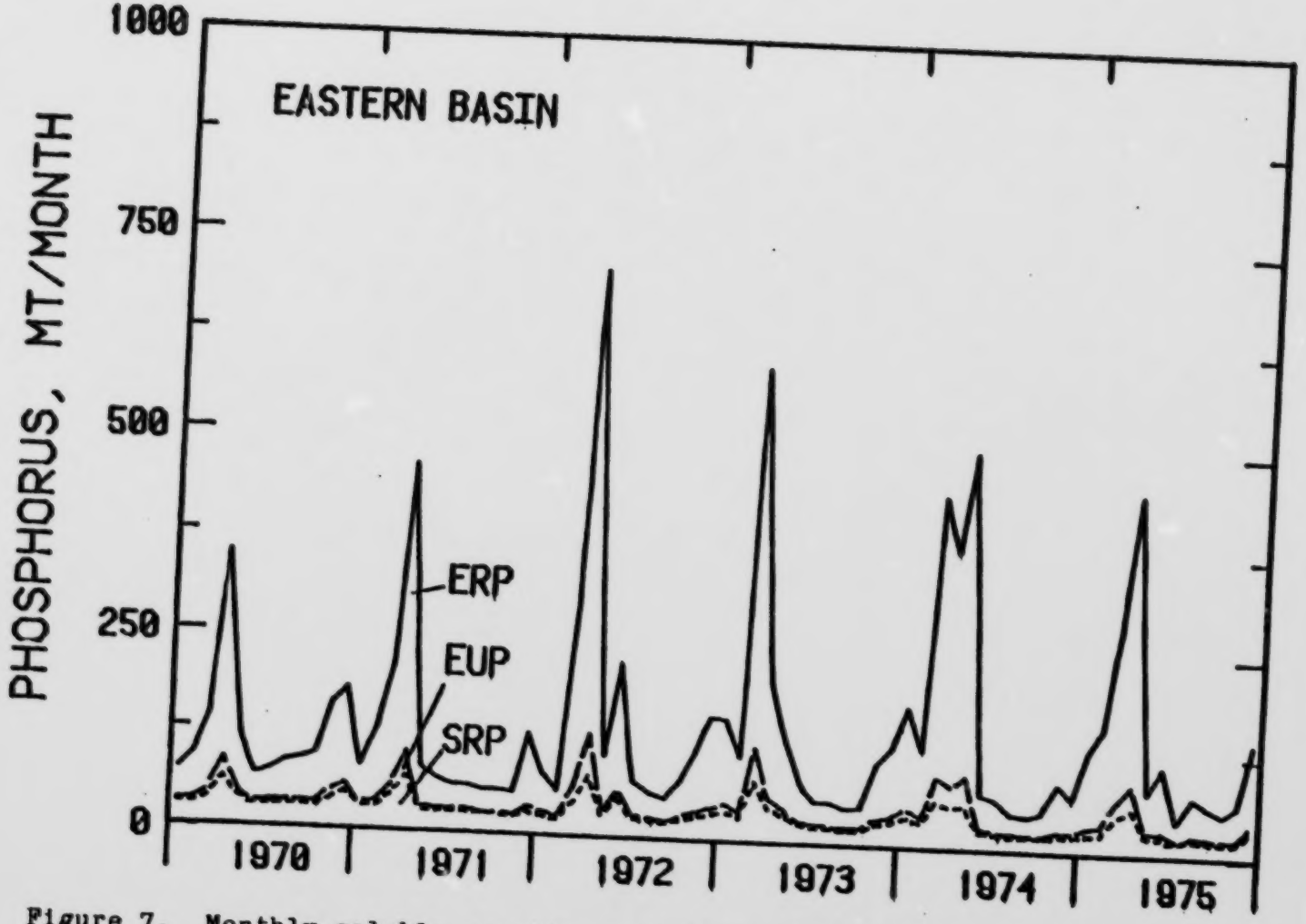

Figure 7. Monthly soluble reactive phosphorus (SRP), external ultimately-available phosphorus (EUP), external refractory phosphorus (ERP), and resultant total phosphorus loadings to the Eastern Basin of Lake Erie, 1970-1975.

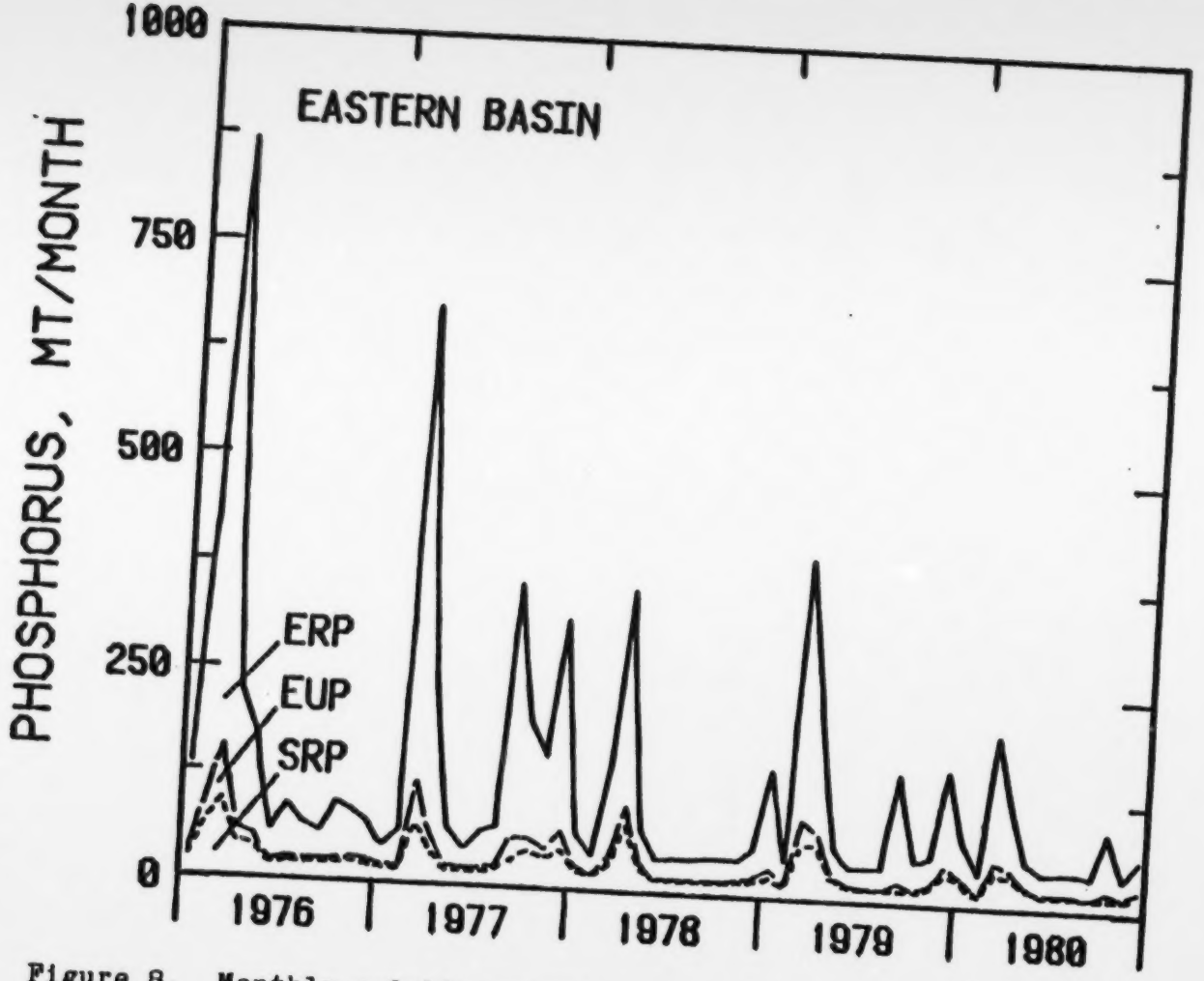

Figure 8. Monthly soluble reactive phosphorus (SRP), external ultimately-available phosphorus (EUP), external refractory phosphorus (ERP), and resultant total phosphorus loadings to the Eastern Basin of Lake Erie, 1976-1980.

Analysis of Lake Erie phosphorus loads was aided by examination of P-form fractionations of 1970-1980 averages (Figures 9-11). Direct point sources, which accounted for only 5.5% of the total P load, contained 50.0% SRP, 31.5% EUP, and 18.5% ERP (Figure 9). The Detroit River (48.3% of the TP load) contained 41.8% SRP, 11.6% EUP, and 46.6% ERP (Figure 9). The bioavailability of the indirect and direct non-point P loads entering Lake Erie were found to be basin-specific. The Western Basin (excluding the Detroit River/St. Clair Basin) (19.4% of the TP load) contained 22.5% SRP, 19.4% EUP, and 58.1% ERP (Figure 10). The Central Basin (18.4% of the TP load) contained 28.5% SRP, 20.0% EUP, and 51.5% ERP (Figure 10). The Eastern Basin (8.4% of the TP load) contained 21.7% SRP, 6.3% EUP, and 72.0% ERP (Figure 11). Overall, the eleven year average of the total phosphorus load to Lake Erie contained 34.4% SRP, 15.3% EUP, and a substantial 50.3% ERP (Figure 11).

The above fractionations were based upon the total P load, however, also of interest is the proportion of EUP in the TEUP load. An average of 23.4% of the total particulate P load to Lake Erie from 1970 to 1980 was calculated to be ultimately-available P (EUP).

While the eleven year average fractionation of the Lake Erie total phosphorus load showed a significant refractory fraction, the change in P fractionation with time was even more revealing. Annual TP loading to Lake Erie from 1970 to 1980 is shown in Figure 12 divided into the forms: SRP, EUP, and ERP. The bioavailable P load, SRP + EUP, decreased approximately linearly during this period while the ERP load fluctuated irregularly. The ERP load may be more dependent upon annual runoff than the bioavailable load. For comparison to the reductions in bioavailable P forms, annual TP loading to Lake Erie is also shown (Figure 13) divided into the sources: indirect point, direct point, and non-point. As a result of municipal treatment facility reductions in total P loads, point source TP loads have also decreased approximately linearly from 1970 to 1980. However, the point source P load decreased at a faster rate than the bioavailable P load. In other words, point source reductions in total phosphorus loading did not result in an equivalent reduction in the bioavailable phosphorus load. This problem would likely be compounded with total phosphorus control measures directed at non-point sources, which contain substantially less ultimately-available phosphorus than point sources.

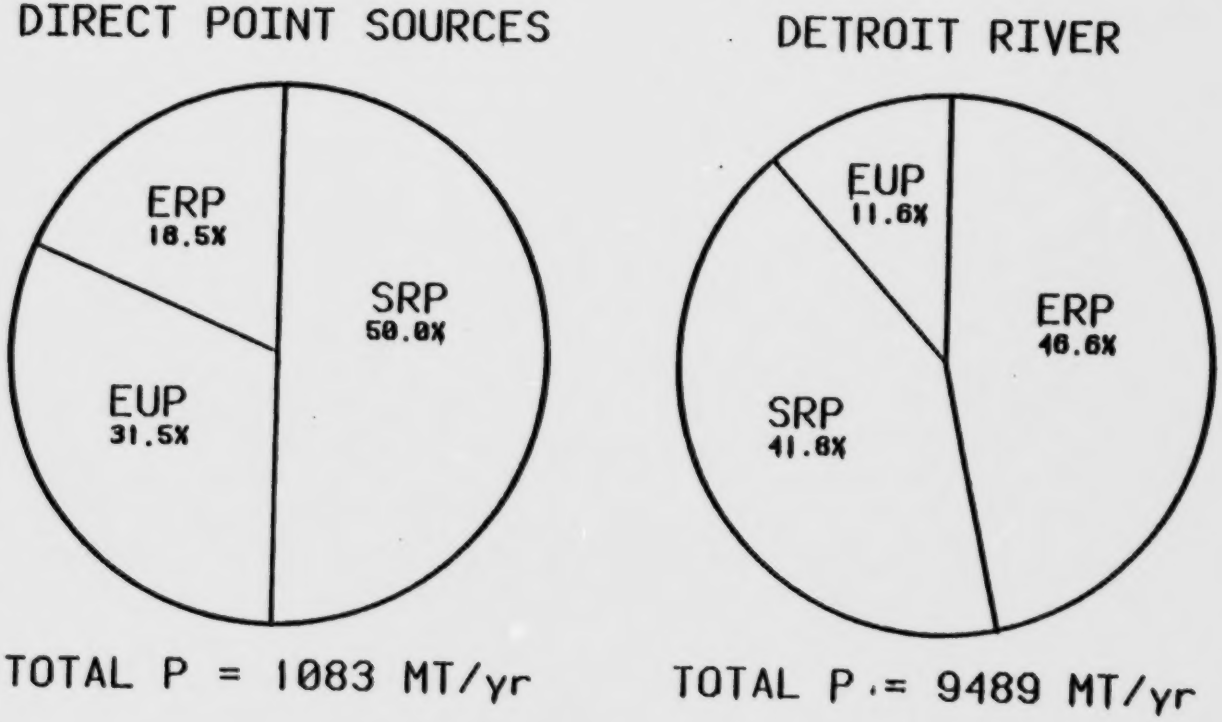

Figure 9. Fractionation of direct point (left) and Detroit River/St. Clair Basin (right) phosphorus loadings to Lake Erie, 1970-1980 averages.

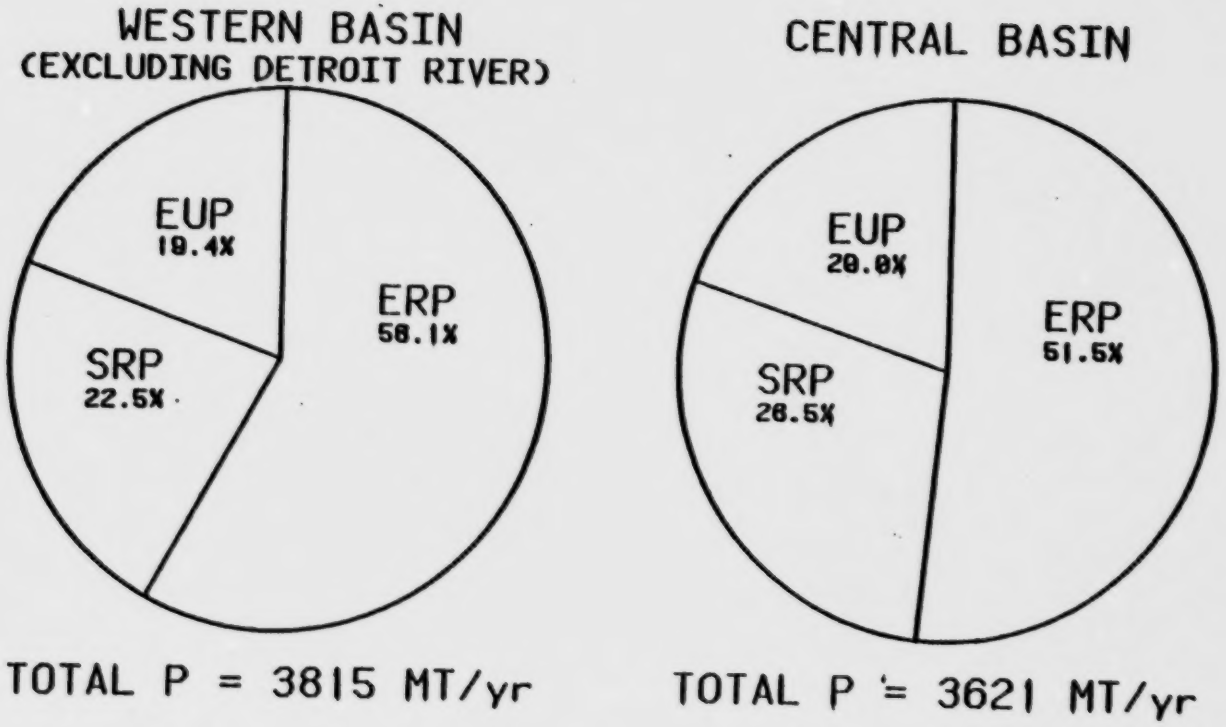

Figure 10. Fractionation of tributary and direct non-point phosphorus loadings to the Western Basin (excluding Detroit River/St. Clair Basin) (left) and Central Basin (right) of Lake Erie, 1970-1980 averages.

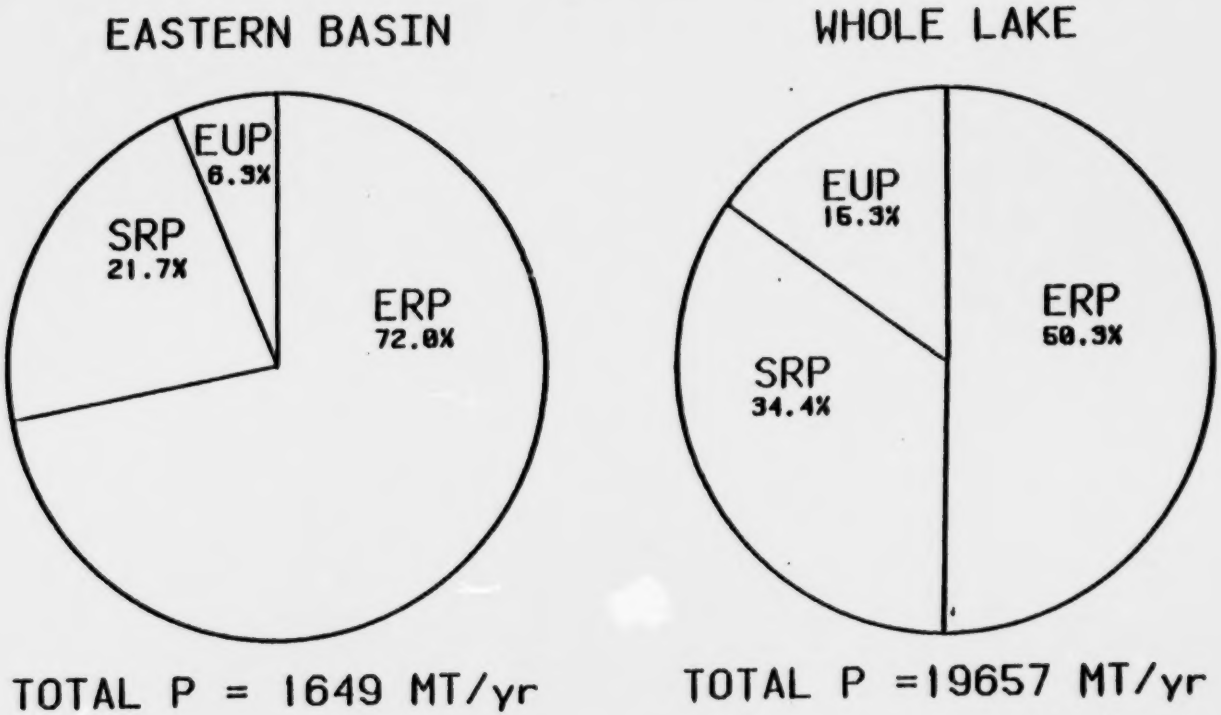

Figure 11. Fractionation of tributary and direct non-point phosphorus loadings to the Eastern Basin of Lake Erie (left) and fractionation of the total phosphorus loadings to Lake Erie (right), 1970-1980 averages.

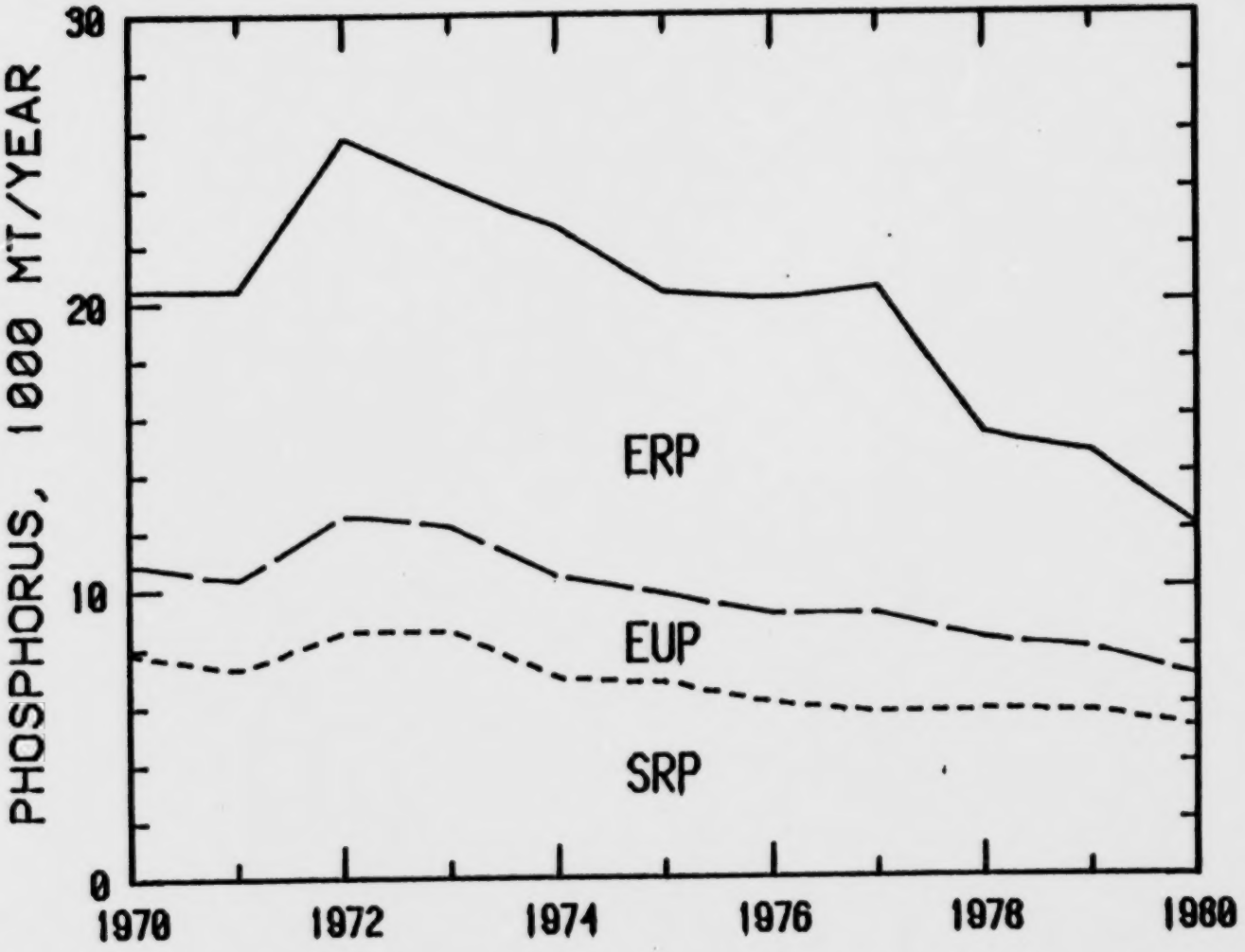

Figure 12. Yearly soluble reactive phosphorus (SRP), external ultimately-available phosphorus (EUP), external refractory phosphorus (ERP), and resultant total phosphorus loadings to Lake Erie, 1970- 1980.

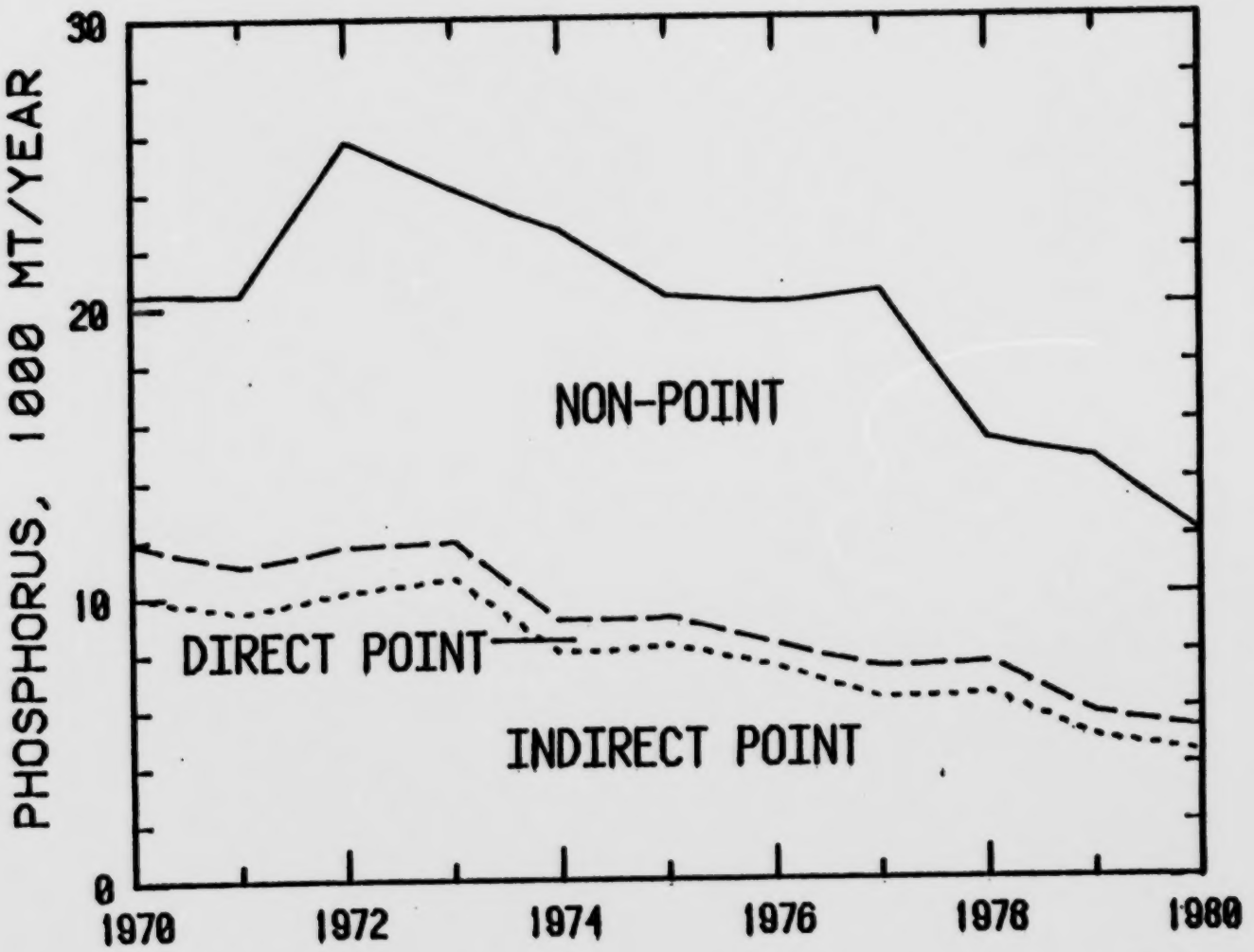

Figure 13. Yearly indirect point phosphorus, direct point phosphorus, non-point phosphorus, and resultant total phosphorus loadings to Lake Erie, 1970-1980.

SECTION 5

LAKE ERIE MODEL DEVELOPMENT

LEM1 was thoroughly discussed in DiToro and Connolly (1980). This chapter briefly examines the physical system, the mass balance approach, and the cycling of nutrients in the water column followed by the model refinement performed for LEM3.

PHYSICAL SYSTEM

Morphometry

Lake Erie and its drainage basin are shown in Figure 14. Lake Erie has a volume of 483 km^3, the smallest of the Great Lakes. It is the shallowest Great Lake, with a mean depth of 18 meters and a maximum depth of 64 meters. The surface area of Lake Erie is 24,720 km^2, the second smallest Great Lake. Of the Great Lakes, only Lake Ontario has a smaller surface area than Lake Erie. The 61,012 km^2 drainage basin area is the smallest of the Great Lakes. This areal figure includes only area draining into Lake St. Clair and Lake Erie, excluding the areas of Lake St. Clair and Lake Erie.

Lake Erie is naturally sectioned into three basins. The Western and Central Basins are separated by a chain of rocky islands. The Central and Eastern Basins are separated by a submerged ridge composed of sand and gravel (Yaksich and Rumer 1980). The flat-bottomed Western Basin has a 3,110 km^2 surface area and a 7.5 meter mean depth. The flat-bottomed Central Basin has a 16,300 km^2 surface area and a 18.3 meter mean depth. The steeply-sloped Eastern Basin has a 6,220 km^2 surface area and a 40 meter mean depth. Additional information on Lake Erie morphology can be found in GLBC (1976a), Sly (1976), and Herdendorf (1982).

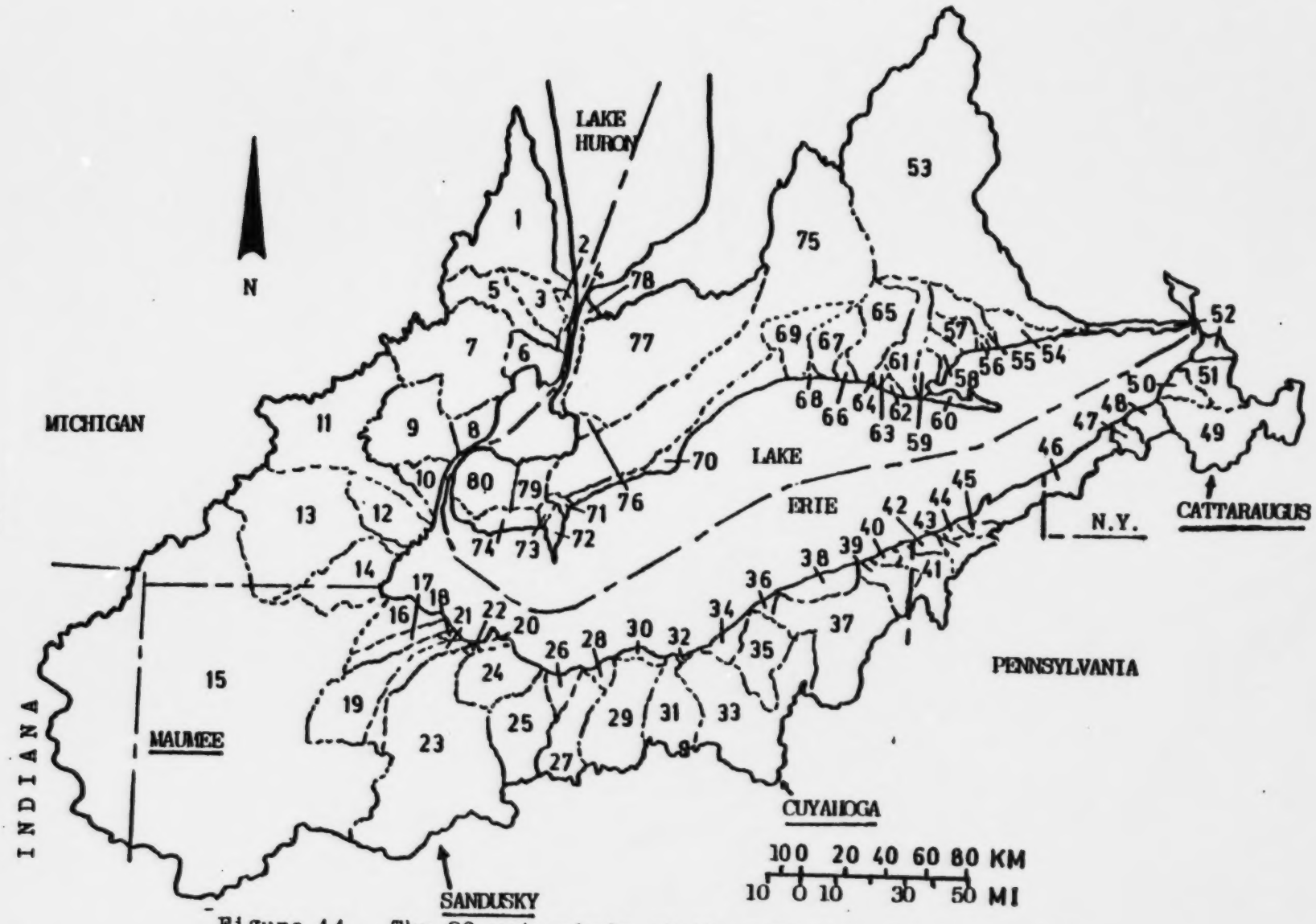

Figure 14. The 80 watersheds of the Lake Erie Drainage Basin. Adapted from Victore (1981).

Model segmentation

The morphometry of Lake Erie formed the basis for the physical segmentation of the Lake Erie nutrient models into six aqueous segments (Figure 15). The mean depth and volume of each segment employed in the models are shown in Table 1. In addition, four sediment segments were modeled. The dimensions of the sediment segments are also shown in Table 1.

TABLE 1. 1970 AND 1975 LAKE ERIE MODEL MORPHOLOGY

Basin	Mean Depth (meter)	Volume (km^3)
Western	7.5	22.6
Central:		
Epilimnion	17.0 (13.0)*	234.6 (186.6)
Hypolimnion	5.0 (9.0)	43.5 (91.5)
Lower Hypolimnion	2.0	7.5
Eastern:		
Epilimnion	17.0 (13.0)	91.9 (73.6)
Hypolimnion	23.0 (27.0)	82.7 (101.0)
Sediment Segments:		
Western Basin	0.05	0.15
Central Basin	0.05	0.28
Central Basin Lower	0.05	0.18
Eastern Basin	0.05	0.27

* Numbers in parentheses represent 1975 resegmentation.

Hydrology

Lake Erie is located between Lakes St. Clair and Ontario. The Detroit River which flows from Lake St. Clair into the Western Basin of Lake Erie contributes 5935 cms (209,600 cfs) which is 95% of the total inflow to the lake. The Maumee River which also flows into the Western Basin carries 113 cms (4000 cfs). Other tributaries contribute 113 cms (4000 cfs) and 85 cms (3,000 cfs) to the Central and Eastern

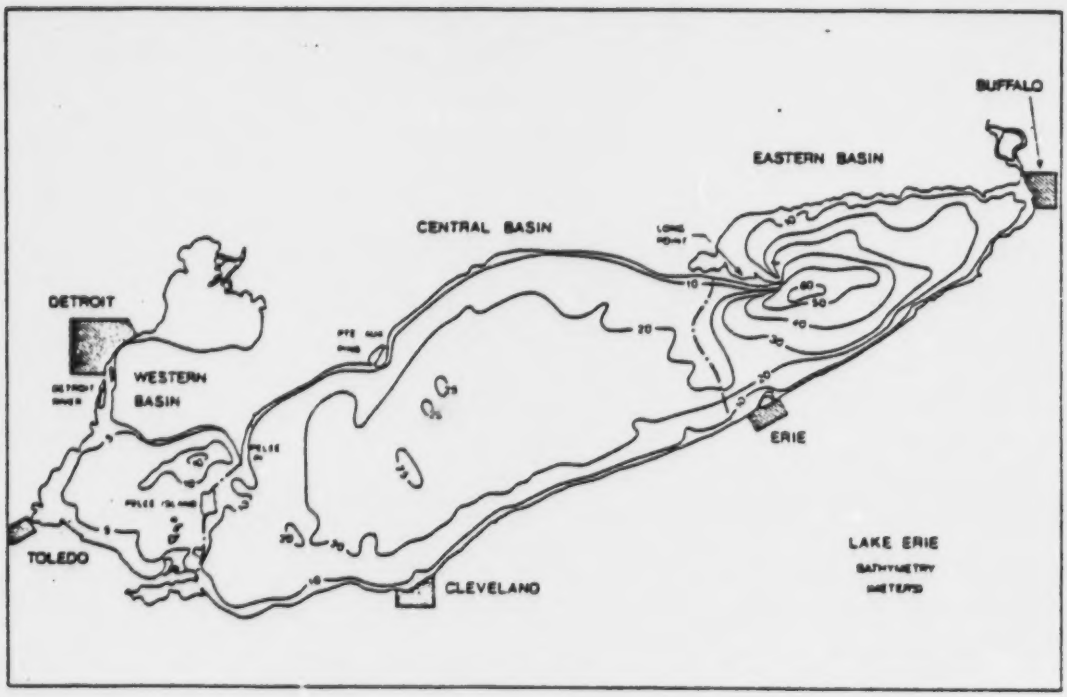

Figure 15. Lake Erie bathymetry. From Sly (1976).

Basins, respectively. The mean hydraulic retention time for Lake Erie is 2.5 years, the shortest of the Great Lakes. Comprehensive information concerning Lake Erie hydrology is found in Brunk (1964), NOAA (1975), and GLBC (1976b).

APPROACH

LEM1 and LEM2 simulated phytoplankton growth, nutrient cycling, and oxygen dynamics by mathematically representing biochemical kinetics and mass transport governed by the conservation of mass. The kinetics regulated the rates of chemical conversions and biological transformations while mass transport independently controlled the movement of chemicals and particulate matter through the water body. LEM1 and LEM2 mathematically simulated the dynamics of the following four biological and eleven chemical state variables:

1. Diatom Chlorophyll-a
2. Non-Diatom Chlorophyll-a
3. Herbivorous Zooplankton Carbon (HZ)
4. Carnivorous Zooplankton Carbon (CZ)
5. Unavailable Nitrogen
6. Ammonia Nitrogen
7. Nitrate Nitrogen
8. Unavailable Phosphorus
9. Soluble Reactive Phosphorus (SRP)
10. Unavailable Silica
11. Soluble Reactive Silica (RSi)
12. Detrital Organic Carbon
13. Dissolved Inorganic Carbon
14. Alkalinity
15. Dissolved Oxygen

The mass balance equation, for state variable ℓ in segment i adjacent to segment k, had the general form:

$$V_i \, (dC_{\ell i}/dt) = E_{ki}(C_{\ell k}-C_{\ell i}) + Q_{ki}C_{\ell k} + S_{\ell i}V_i + W_i \qquad (2)$$

where

V_i = volume of segment i

C_ℓ = concentration of state variable ℓ in segment i or k

E_{ki} = bulk dispersion coefficient between segments k and i

Q_{ki} = advective flow from segment k to segment i

$S_{\ell i}$ = sum of sources and sinks for state variable ℓ

W_i = sum of external loadings of state variable ℓ

This equation shows that bulk dispersion and advection controlled the mass transport through the water body. The sum of the source/sink terms, S, were the biochemical conversions and transformations; S represents the nutrient cycling in the water column.

NUTRIENT CYCLING

Phosphorus

Phosphorus was present in LEM1 and LEM2 in four biological and two chemical forms. These biological and chemical forms, listed above, are shown LEM1 and LEM2 on the left side of Figure 16 represented by the boxes. The inter-actions of the P forms are represented by the thin arrows between boxes. Ultimately-available P which was not directly utilizable by phytoplankton was converted to bioavailable SRP at a temperature dependent, first-order rate (0.03/day at 20 C). Phosphorus was transferred through the food chain via phytoplankton uptake of SRP, herbivorous zooplankton consumption of phytoplankton and carnivorous zooplankton consumption of herbivore zooplankton. Phosphorus was cycled back to both chemical forms, ultimately-available P and SRP, via phytoplankton endogenous respiration and non-predatory mortality and via zooplankton excretion and death. SRP and ultimately-available P were input via external loads shown as thick arrows in Figure 16. In addition, atmospheric SRP was input via boundary concentration conditions. Boundary conditions (mass/unit volume) were equivalent to mass loadings since they were associated with water flow (volume/unit time).

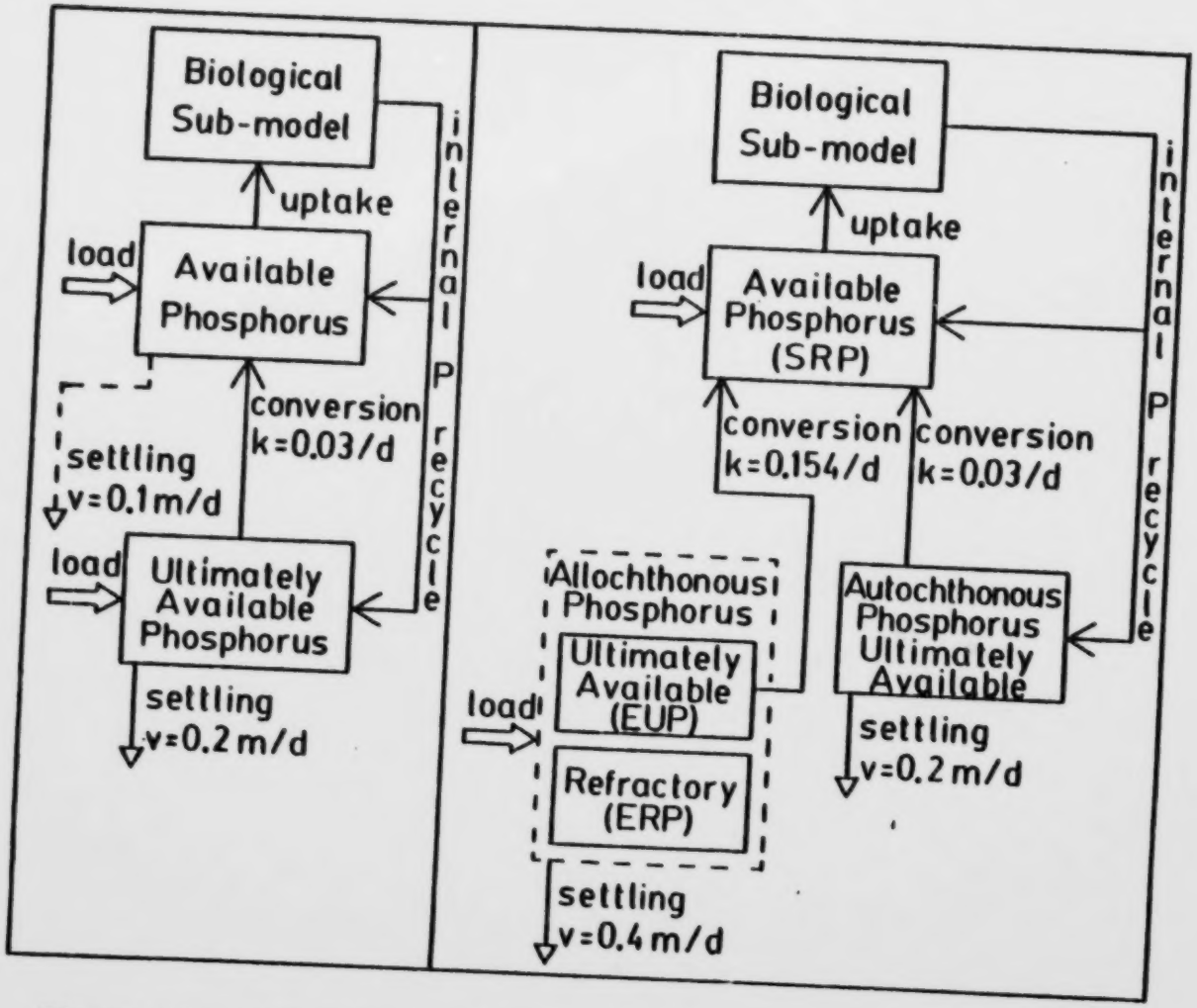

Figure 16. Comparison of LEM1, LEM2 (left) and LEM3 (right) phosphorus kinetics, loading, and settling.

Nitrogen

Nitrogen was present in four biological and three chemical forms. Unavailable N which was not directly utilizable by phytoplankton was converted to ammonia nitrogen which was oxidized to nitrate nitrogen. Both of these reactions occurred at temperature dependent, first-order rates. Nitrite nitrogen was not explicitly modeled since nitrite is rapidly converted to nitrate in water bodies and, therefore, was considered to be an insignificant nitrogen species. Ammonia and nitrate were utilized by phytoplankton for growth at individual rates proportional to their concentration relative to the total bioavailable nitrogen concentration. Nitrogen was transferred through the food chain and cycled back to the three chemical species via the phosphorus pathways. Unavailable particulate N, ammonia, and nitrite were input via external loads. Atmospheric N (ammonia) was also input via boundary concentration conditions.

Silica

Silica was present in one biological (diatoms) and two chemical forms. Unavailable silica which was not directly utilizable by diatoms was converted to bioavailable soluble reactive silica at a temperature dependent, first-order rate. Available silica was utilized only by diatoms. Silica transferred to the herbivorous zooplankton by phytoplankton predation was excreted as unavailable silica. Silica was also cycled back as unavailable silica via diatom endogenous respiration and non-predatory mortality. Soluble reactive silica was input via external loads. Unavailable silica was input by boundary concentration conditons.

Dissolved oxygen

Dissolved oxygen was utilized by plankton respiration, nitrification and oxidation of detrital organic carbon. Dissolved oxygen was regenerated by phytoplankton photosynthesis and atmospheric reaeration. Dissolved oxygen was input by boundary concentration conditions.

REFINEMENT

Theory

LEM1 and LEM2 made no distinction between the release of available P (SRP) from allochthonous suspended sediment-P and the conversion of autochthonous detrital biomass P to available P. Recent research (DePinto et al. 1981, Young et al. 1982, Martin 1983) indicated that there were subtle differences between these processes; both the rate of SRP generation and the extent of SRP release differed.

Many studies of phosphorus dynamics in tributaries and lakes have been performed. Detailed examination of this literature will not be presented herein. Numerous reviews of research concerning phosphorus dynamics in water bodies already exist (DePinto 1979, Golterman 1975, Jewell 1968, Johannes 1968, Martin 1983). Instead only some of the research pertinent to the differences between the phosphorus dynamics of allochthonous and autochthonous material in the water column are discussed.

Allochthonous Material--

Several researchers have utilized bioassays based on algal P content or algal biomass to estimate the amount of available P released from allochthonous material. Low availability of allochthonous material was found by Cowen and Lee (1976a,b), Dorich and Nelson (1978), Dorich et al. (1980), Logan (1978), and Porter (1975). However, none of these investigations measured actual P uptake or available P release rates.

Veroff et al. (1978) measured the rate at which phytoplankton incorporated P from river sediments from Lake Erie tributaries. A mass balance on total P and total inorganic solids was utilized to determine the P release rate. Veroff et al. (1978) determined a slow, linear P availability rate from 0.2% to 0.4% P/day.

In contrast, DePinto et al. (1981) measured fast, first-order P release rates from 0.07 to 0.22/day (mean, 0.154/day) (base e) with suspended sediments from tributaries of Lakes Erie and Ontario. Their procedure utilized the Dual Culture Diffusion Apparatus (DCDA), which permited a direct measure of P uptake by P-starved algae, and which minimized procedural error (DePinto 1982). In addition, they found that from 0 to 47% (mean, 21.8%) of the total unavailable particulate P (TEUP) from five lower Great Lakes tributaries was ultimately-available (EUP).

Young et al. (1982) utilized the DCDA procedure to examine the rate and extent of P release from particulates in municipal wastewater. They measured fast, approximately

first-order available P release rates from 0.08 to 0.41/day (mean, 0.27/day) (base e). In contrast to the low average EUP:TEUP ratio found in river sediments, Young et al. (1982) found that an average of 63% of TEUP was EUP in municipal wastewater particulates.

Autochthonous material--

The rate and extent of P release from decaying algae has been measured (DePinto and Veroff 1977, DePinto et al. 1980). DePinto and Veroff (1977) measured P regeneration rates from bacteria-inoculated batch cultures of decaying algae from 0.06 to 0.39 ug P/mg algae-day. The higher rates were associated with cultures with initially high cellular P levels. Essentially no available phosphorus was regenerated in bacteria-free cultures. DePinto and Veroff (1977) found that from 31 to 95% (mean, 74%) of cellular algal P becomes available within 45 days. DePinto et al. (1980) utilized the DCDA and estimated approximately first-order rate coefficients which varied from 0.01 to 0.05/day (base e). The higher rates were measured in cultures with initially high cell P levels and in cultures subjected to bacterial inoculation. The rate of P release from detrital phytoplankton also depends on other environmental factors, including temperature, light, pH, dissolved oxygen, and algal species.

P-release sub-model comparison

For allochthonous material, LEM1 and LEM2 utilized a slow release of SRP from the total particulate P while LEM3 utilized a fast release of SRP from an available fraction (FA) of the total particulate P. The significance of the differences in the amount of SRP released from allochthonous particulate P was examined by comparing the predictive capabilities of the sub-models.

Both methods for predicting the cumulative available P released from allochthonous suspended sediments can be mathematically represented as,

$$BAPP(t) = FA \quad TEUP(1-\exp(-Kt)) \qquad (3)$$

where

BAPP(t) = cumulative available phosphorus released from the sediments (ug P/100 mg dry sediment)

TEUP = total external unavailable P (ug P/100 mg dry sediments)

FA = ultimately-available fraction of TEUP

K = rate of release of available P from sediments (1/day)

t = time of sediments in water column (days)

The two sub-models utilized the same value for TEUP, however, different values were used for the coefficients, FA and K. The divergence in the predictions of the sub-models was significant.

As an example illustrating the difference in the predicted cumulative available P released from suspended sediments consider Maumee River sediments sample number 17 (DePinto et al. 1981). The cumulative available P released as predicted by the two sub-models is plotted in Figure 17 with the directly-measured cumulative available P released from sample number 17. For sample number 17, TEUP = 115 ug P/100 mg-dry sediments. The DiToro and Connolly method, based on total external unavailable P, would utilize FA = 1.00. In contrast, the DePinto et al. (1981) method, based on the ultimately-available fraction of the total external unavailable P in sample number 17, used FA = 0.256. The DiToro and Connolly method used K = 0.03/day even though this value was based primarily on available P regeneration from decaying algae. More realistically, the DePinto et al. (1981) method utilized K = 0.171/day based on the directly-measured release of SRP from particulate P in Maumee River suspended sediments sample no. 17. After approximately 8 days the DiToro and Connolly method overpredicted the directly-measured data and became progressively worse as time increased. In contrast, the DePinto et al. (1981) method reproduced the data well.

Some samples would show even more deviation between the two methods. This would be especially true for suspended sediment samples from the Cattaraugus River in the Eastern Basin of Lake Erie since the bioavailable fraction of TEUP was extremely small (0.08). A similar, although less dramatic, effect would be observed with direct point particulate P which contains a high bioavailable fraction of TEUP (0.63).

Obviously, the effect of the DiToro and Connolly method, when incorporated in water quality models, would be to overpredict SRP sources in the water column when the unavailable P resides in the water column for longer than a week or two. The problem that the DiToro and Connolly method causes in a modeling context is that, in order to calibrate the model, other coefficients might need to be adjusted to compensate for the above discrepancy. Indeed, DiToro and Connolly (1980) found it necessary to include a net apparent settling velocity for SRP, of 0.1 meter/day in order to effect a reasonable calibration of SRP, as is shown in Section 6.

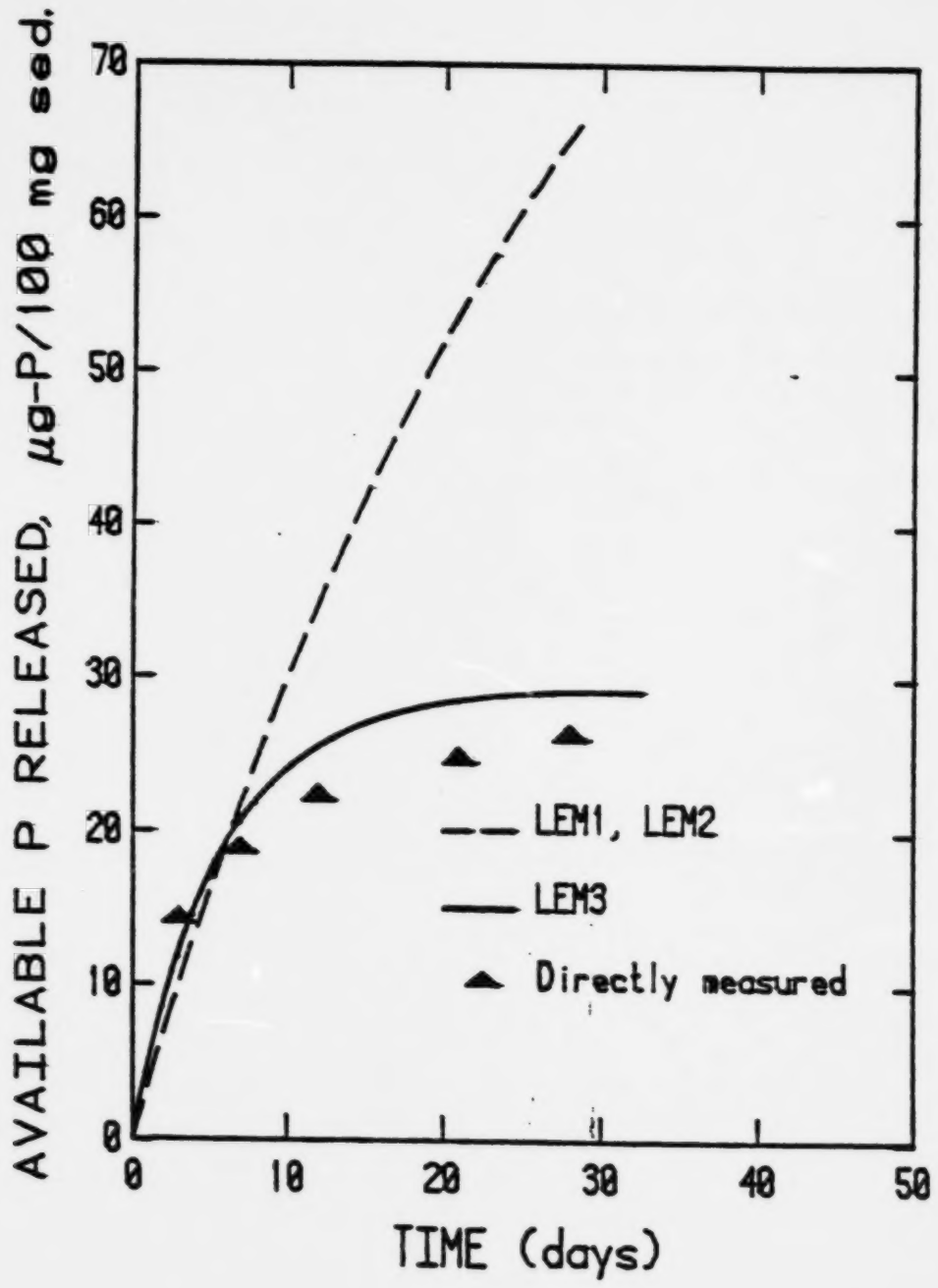

Figure 17. Comparison of LEM1/LEM2 and LEM3 sub-model predictions with directly-measured data for Maumee River sediments sample no. 17. Adapted from DePinto et al. (1981).

Mathematical description

The entire set of source/sink terms used for the aqueous segments in LEM3 for soluble reactive P, autochthonous ultimately-available P, and allochthonous ultimately-available P are shown in Table 2. The corresponding reaction rates are shown in Table 3. The rate constants and other coefficients for the reaction rates are shown in Table 4. The discussion here was limited to the model refinements; discussions of remaining sources and sinks can be found in DiToro and Connolly (1980) and DiToro and Matystik (1980).

TABLE 2. SOURCE/SINK TERMS FOR PHOSPHORUS SYSTEMS IN AQUEOUS SEGMENTS IN REFINED LAKE ERIE MODEL, LEM3

Soluble Reactive Phosphorus Source/Sink Term

$$S_9 = -PCHL \cdot R_1 + PCHL \cdot FAP \cdot R_2 + (1-\beta)PCHL \cdot FAP \cdot R_3 + (1-\varepsilon_c)PC \cdot FAP \cdot R_4 + PC \cdot FAP \cdot R_5 + R_{10} + R_{16} \quad (4)$$

Autochthonous Ultimately-Available Phosphorus Source/Sink Term

$$S_8 = PCHL(1-FAP)R_2 + (1-\beta)PCHL(1-FAP)R_3 + (1-\varepsilon_c)PC(1-FAP)R_4 + PC(1-FAP)R_5 - R_{10} \quad (5)$$

Allochthonous Ultimately-Available Phosphorus Source/Sink Term

$$S_{16} = -R_{16} \quad (6)$$

TABLE 3. REACTION RATE FORMULATIONS FOR PHOSPHORUS SYSTEMS IN AQUEOUS SEGMENTS IN LEM3

Phytoplankton Growth Rate

$$R_1 = K_1\theta_1^{(T-20)}\, r(I/Is)\, ([SRP]/(Kmp + [SRP]))\, ([AN]/(KmN + [AN]))\, ([RSi]/(KmSi + [RSi]))\, [TCH] \quad (7)$$

Phytoplankton Respiration and Non-Predatory Mortality

$$R_2' = K_2\theta_2^{(T-20)}\, [TCH] \quad (8)$$

Herbivorous Zooplankton Growth Rate

$$R_3 = K_3 T(Kmg/(Kmg + [TCH]))\, [TCH]\, [HZ] \quad (9)$$

Carnivorous Zooplankton Growth Rate

$$R_4 = K_4 T\, [HZ]\, [CZ] \quad (10)$$

Zooplankton Respiration Rate

$$R_5 = K_5\theta_5^{(T-20)}\, [Z_T] \quad (11)$$

Autochthonous Ultimately-Available P to SRP Conversion Rate

$$R_{10} = K_{10}\theta_{10}^{(T-20)}\, ([TCH]/(Kmr + [TCH]))\, [IUP] \quad (12)$$

Allochthonous Ultimately-Available P to SRP Release Rate

$$R_{16} = K_{16}\theta_{16}^{(T-20)}\, ([TEUP] - [ERP]) \quad (13)$$

TABLE 4. RATE CONSTANTS AND OTHER COEFFICIENTS IN AQUEOUS SEGMENTS IN LEM3

Description	Notation	Value		Units
		Diatom	Non-diatom	
Light reduction factor	r(I/Is)	Non constant		None
Saturated growth rate	K_1	2.1	1.6	1/day
Temperature coefficient	θ_1	1.04	1.13	None
Half saturation constant for phosphorus	Kmp	1.0	1.0	ug PO_4-P/L
Half saturation constant for nitrogen	KmN	25.0	25.0	ug N/L
Half saturation constant for silica	KmSi	30.0	0.0	ug Si/L
Phosphorus to chlorophyll-a ratio	PCHL	0.5	0.5	ugPO_4-P/ug Chl-a
Endogenous respiration rate (phytoplankton)	K_2	0.075	0.075	1/day
Temperature coefficient	θ_2	1.08	1.08	None
Available-P fraction of respired phytoplankton	FAP	0.4	0.4	None
Assimilation limitation factor = ϵ_h Kmϵ/(Kmϵ+ TCH)	β	Non constant		None
Filtering rate (herbivorous zooplankton)	K_3	0.035		L/mg C/day-C

(continued)

TABLE 4. Continued

Description	Notation	Value	Units
Half saturation constant for filtering rate limitation (herbivorous)	Kmg	15.0	ug Chl-a/L
Half saturation constant for assimilation rate limitation (herbivorous)	Kmε	10.0	ug Chl-a/L
Maximum assimilation efficiency (herbivorous)	ε_c	0.6	None
Filtering rate (carnivorous zooplankton)	K_4	0.05	L/mg C/day-C
Assimilation efficiency (carnivorous)	ε_h	0.6	None
Phosphorus to carbon ratio	PC	5.0	ug PO_4-P/mg C
Zooplankton respiration rate	K_5	0.02	1/day
Temperature coefficient	θ_5	1.045	None
Internal unavailable phosphorus mineralization rate	K_{10}	0.03	1/day
Temperature coefficient	θ_{10}	1.08	None
Half saturation constant for chlorophyll-a limitation	Kmr	5.0	ug Chl-a/L
External ultimately-available phosphorus mineralization rate	K_{16}	0.154	1/day
Temperature coefficient	θ_{16}	1.02	None

Refinements made to LEM3 were made only to the mathematical representation of phosphorus dynamics. Figure 16 illustrates the only differences between LEM1, LEM2 (left), and LEM3 (right). In LEM1 and LEM2 the total external load of particulate P and the ultimately-available P internally recycled from organisms were both treated as having the same characteristics. In contrast, LEM3 made a distinction between these two forms of unavailable P; allochthonous and autochthonous unavailable P were represented separately.

LEM1 and LEM2 utilized the same release rate, K, and extent of SRP release, FA, for available P released from allochthonous particulate P and available P converted from autochthonous ultimately-available P, K = 0.03/day (at 20 C) and FA=1.00. Although reasonably representative of autochthonous algal decay, these coefficients poorly reflect the characteristics of allochthonous suspended sediments and particulate P in municipal wastewater effluent.

In contrast, LEM3 utilized individual coefficients for autochthonous and allochthonous unavailable P, reflective of their distinct bioavailability characteristics. For autochthonous P, K = 0.03/day (DePinto and Verhoff 1977) and FA = 1.00. For allochthonous particulate P, K = 0.154/day (DePinto et al. 1981). The extent of SRP release from allochthonous material varied depending upon the source (Table 5).

TABLE 5. BIOAVAILABLE FRACTIONS OF TOTAL EXTERNAL UNAVAILABLE PHOSPHORUS UTILIZED IN LEM3

Input Source	(EUP/TEUP)x100	Data Source
Municipal wastewater	63	Young et al. (1982)
Tributaries:		
Detroit River	20	Martin (1983)
Western Basin	25	DePinto et al. (1981)
Central Basin	28	DePinto et al. (1981)
Eastern Basin	08	DePinto et al. (1981)

For LEM3, internal ultimately-available P (IUP) originated from detrital biomass and was converted to SRP at a temperature dependent, saturating rate (0.03/day at 20 C). The conversion from IUP to SRP was mathematically represented as,

$$S_{10} = K_{10}\theta_{10}^{(T-20)} \left([TCH]/(Kmr + [TCH]) \right) [IUP] \quad (14)$$

where

S_{10} = sink term for IUP and source term for SRP (mg P/L-day)

K_{10} = rate coefficient for the conversion of IUP to SRP (/day)

θ_{10} = temperature coefficient for K_{10} = 1.08

T = water column temperature (C)

[TCH] = concentration of total chlorophyll-a (ug Chl-a/L)

Kmr = half saturation constant for chlorophyll-a limitation

[IUP] = concentration of IUP (mg P/L)

The conversion of autochthonous detrital P was represented as a saturating function of total chlorophyll-a concentration to improve the predictability of SRP release compared to that obtained with a first- or second-order representation (DiToro and Matystik 1980). The effect of utilizing a saturating function was to reduce the conversion rate at low total chlorophyll-a concentration and to increase the rate at high total chlorophyll-a concentration while maintaining a maximum rate (0.03/day) even at very high total chlorophyll-a concentration. The reasoning behind the assumption that the rate of SRP release from autochthonous detrital P was dependent upon total chlorophyll-a concentration was based on research by, amoung others, Menon et al. (1972). As chlorophyll-a concentration increases the major source of carbon utilized by bacteria, algal detritus, increases. Since the conversion of detritus is mediated by bacteria, as chlorophyll increases bacterial biomass increases resulting in a higher rate of SRP release from autochthonous ultimately-available P. In addition, dissolved organic P is metabolized by some algal species, the detrital P conversion rate increasing as chlorophyll-a concentration increases.

A basin-specific fraction, FA, of TEUP was considered to be EUP. The remaining fraction was considered to be unavailable to algae (ERP). EUP was converted to SRP at a temperature dependent, first-order rate (0.154/day at 20 C). The conversion from EUP to SRP was mathematically represented as,

$$S_{16} = K_{16}\theta_{16}^{(T-20)} ([TEUP] - [ERP]) \quad (15)$$

where

S_{16} = sink term for EUP and source term for SRP (mg P/L-day)

K_{16} = rate coefficient for the conversion of EUP to SRP (/day)

θ_{16} = temperature coefficient for K_{16} = 1.02

T = water column temperature (C)

[TEUP] = concentration of total external unavailable P (mg P/L)

[ERP] = concentration of external refractory P (mg P/L)

Phosphorus settling

Particulate Phosphorus--

Particle settling velocities control particle residence times in the water column and, therefore, affect the amount of P released from the particle (Armstrong et al. 1979). LEM1 and LEM2, neither of which distinguished between allochthonous and autochthonous unavailable phosphorus, settled unavailable particulate phosphorus from the water column at 0.2 meters/day, the value used by DiToro and Connolly (1980). However, research by Kwolek (1982) showed that there are differences in the settling velocities of allochthonous and autochthonous particulate P.

Kwolek (1982) found the average of the median settling velocities for the Sandusky, Maumee, Cyuahoga, and Honey Creek Rivers were 0.27, 0.52, 0.60, and 0.15 meters/day, respectively. Therefore, LEM3 assumed that allochthonous and autochthonous unavailable PP settled at different rates. The average of the values measured by Kwolek, 0.4 meters/day, was used for the allochthonous unavailable P settling velocity through the water column in LEM3. Autochthonous particulate P was settled at 0.2 meters/day in LEM3.

Soluble Phosphorus--

LEM1 settled soluble reactive phosphorus from the water column at one-half of the value of the settling velocity coefficients utilized for particulate settling. To effect a reasonable calibration for Lake Erie, DiToro and Connolly (1980) found it necessary to settle the dissolved form of phosphorus, SRP, from the water column at 0.1 meter/day, as

indicated by the dashed line below the SRP box in Figure 16. DiToro and Connolly did not include a specific mechanism for SRP loss in their model nor did they attempt to verify this concept. DiToro and Connolly model simulations are shown in Section 6 with (LEM1) and without (LEM2) utilizing SRP settling as a mechanism for removing SRP from the water column to illustrate the dramatic effect of including SRP settling in the model framework. The lack of SRP settling in LEM2 was the only difference between LEM1 and LEM2. LEM3 assumed that SRP does not settle from the water column.

SECTION 6

LAKE ERIE MODEL SIMULATIONS

INTRODUCTION

In order to evaluate the effect of the model modification on in-lake phosphorus dynamics, simulations of LEM1, LEM2, and LEM3 were compared. The models were described and contrasted in Section 5.

All three models utilized the same P loading data (D.A. Melfi, U.S. Army Corps of Engineers, Buffalo District 1982), however, the loads were fractionated into different forms. The external P load for LEM1 and LEM2 consisted of two forms, SRP and ultimately-available P. The external P load for LEM3, more realistically, consisted of three forms, SRP, EUP, and ERP, as described in Section 4.

The P loading data used in this comparison were not the same data as were used by DiToro and Connolly to calibrate their model. The Corps revised their estimates of total and orthophosphate loadings to Lake Erie subsequent to the DiToro and Connolly modeling effort.

LEM1 and LEM2 were not recalibrated to the P loading data utilized. Model coefficients utilized by DiToro and Connolly (1980) were used for LEM1 and LEM2. However, LEM2 did not employ SRP settling from the water column. LEM3 was not calibrated for this research. LEM3 utilized model coefficients determined by DiToro and Connolly (1980) for those state variables which were common to the models. For the state variables unique to LEM3 (TEUP and ERP) unadjusted empirical coefficients obtained from laboratory experimentation (DePinto et al. 1981, Kwolek 1982, Young et al. 1982, Martin 1983) were utilized. Therefore, the differences in P dynamics in the three models were readily compared. Before examining the comparitive simulations, the distribution of the forms of phosphorus in the Western Basin of Lake Erie in 1970 is discussed.

PHOSPHORUS SPECIES DISTRIBUTION

The distribution of ERP, EUP, IUP, total phytoplankton P (PHYTO-P), and SRP and the resultant TP, as modeled by LEM3, in 1970 in the Western Basin is shown in Figure 18. SRP was the most variable phosphorus form. SRP, EUP, and ERP loading in the Western Basin in 1970 were highest during the spring months of March, April, and May (Table A.1). There were resultant peaks during this period, in the otherwise constant, ERP and EUP concentrations. The SRP concentration was extremely high due to high SRP and EUP loading and limited uptake by phytoplankton. Phytoplankton-P also peaked slightly although it was apparent that the phytoplankton growth was not limited by phosphorus during the spring. During the late summer and early fall a large phytoplankton peak was apparent with a resultant depletion of SRP. Autochthonous unavailable P concentration increased due to phytoplankton excretion and respiration. During the winter phytoplankton-P decreased. Internal unavailable P decreased due to the decrease in phytoplankton excretion and respiration. SRP increased due to limited phytoplankton uptake.

COMPARATIVE SIMULATIONS

Model simulations for 1970 and 1975 are shown in Figures 19-24. Symbols represent the mean of many segment water samples plus/minus one standard deviation. The lines are the model simulations. LEM1, the DiToro and Connolly model utilizing SRP settling, is shown as a dashed line. LEM2, the DiToro and Connolly model without SRP settling, is shown as a dotted line. LEM3, the model reported here, is represented as a solid line. The simulations of all three models generally showed the same trends, however, the magnitudes of the predictions were often substantially different.

Soluble reactive phosphorus

SRP simulations for 1970 are shown in Figure 19 and SRP simulations 1975 are shown in Figure 20. All three models predicted higher spring SRP concentrations than the observed SRP data indicate in all segments in both 1970 and 1975. Assuming that the data are accurate it was apparent that the SRP mechanism was not fully represented in any of the models during the spring. With over-determined models such as these, there are numerous possible sources of error, two likely causes were considered.

Firstly, cellular phosphorus content was tracked in these models by a constant cellular P:total chlorophyll-a ratio.

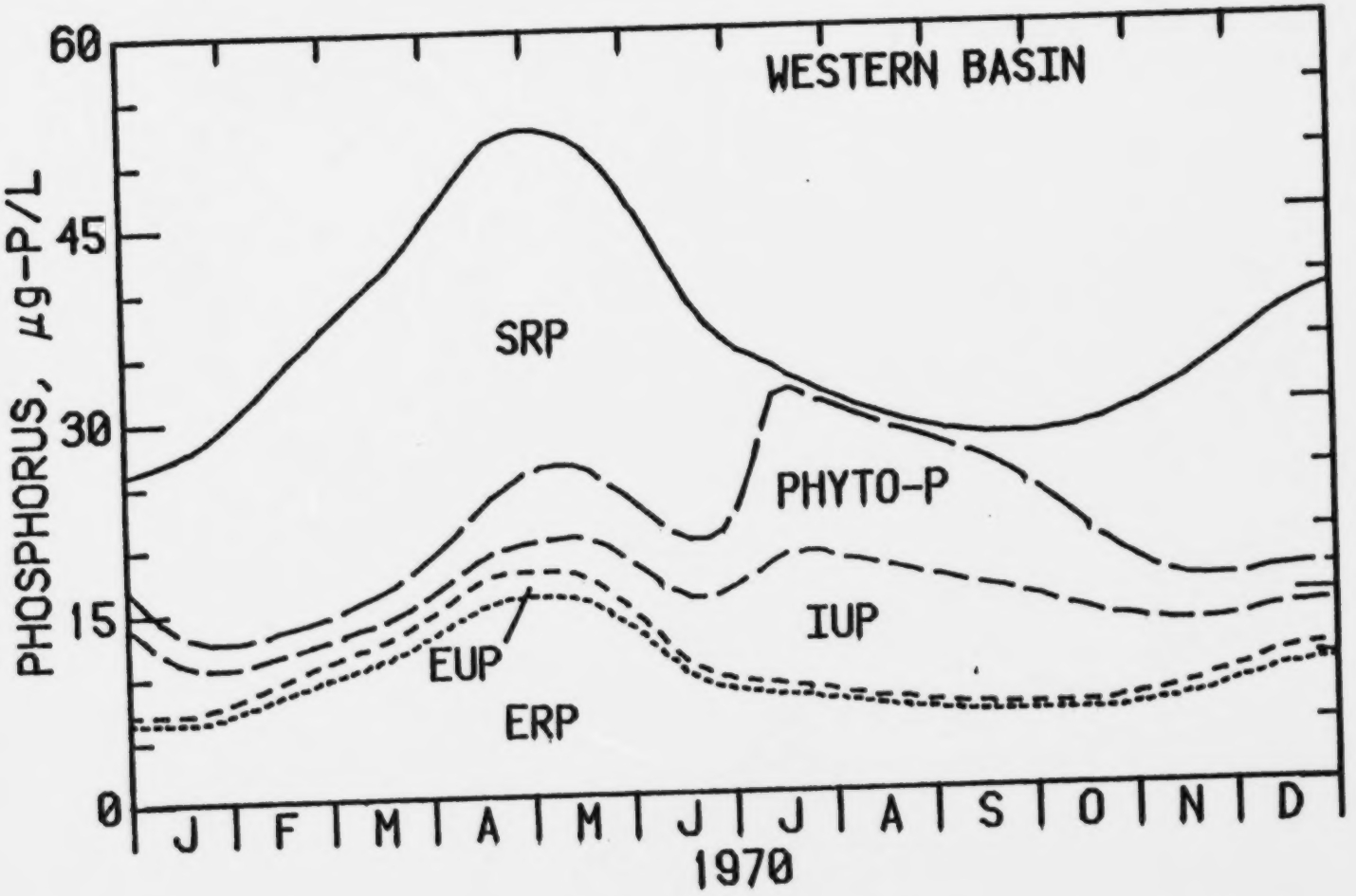

Figure 18. LEM3 phosphorus species distribution in the Western Basin of Lake Erie in 1970, external refractory phosphorus (ERP), external ultimately-available phosphorus (EUP), internal ultimately-available (IUP), phytoplankton phosphorus (PHYTO-P), soluble reactive phosphorus (SRP), and the resultant total phosphorus are diagramed.

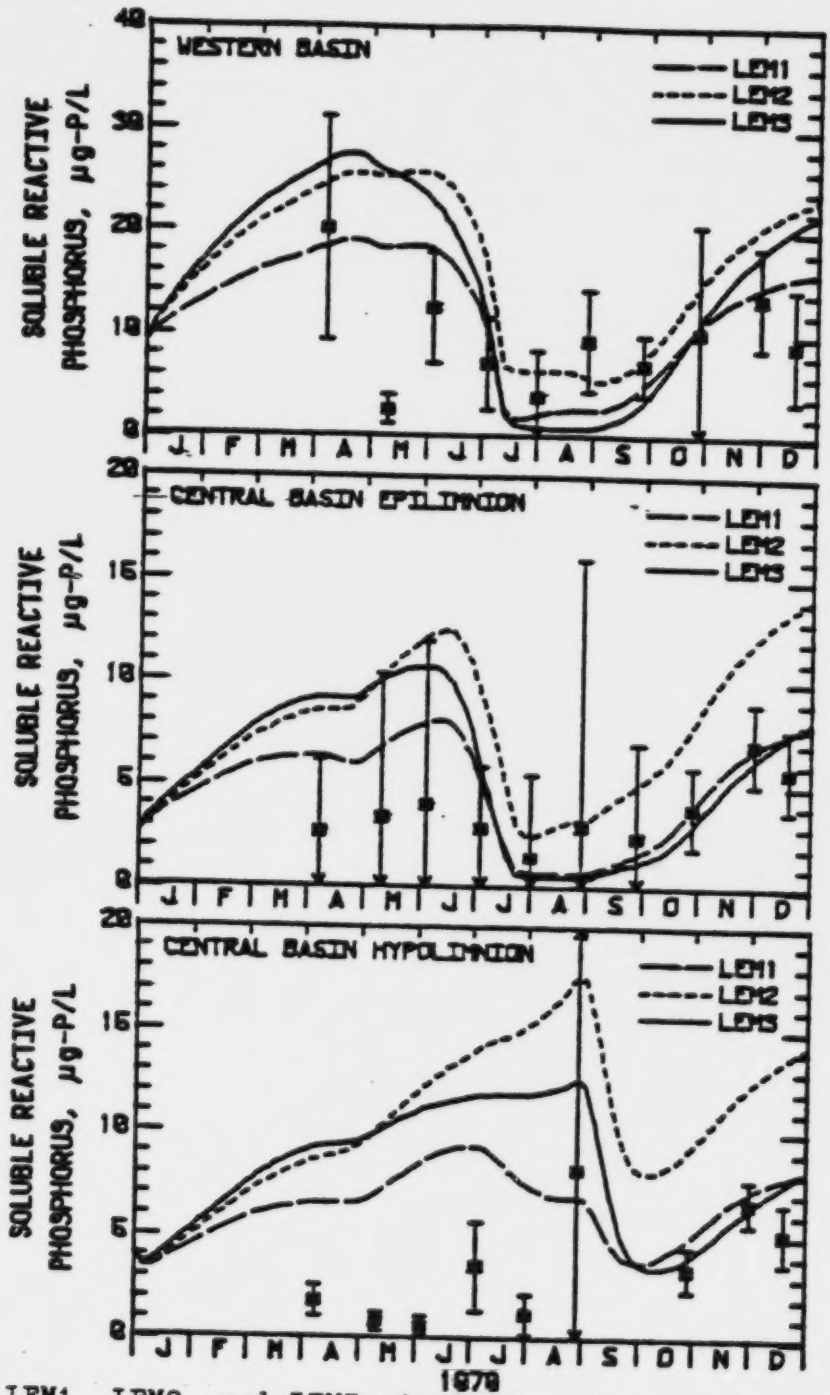

Figure 19. LEM1, LEM2, and LEM3 simulations for soluble reactive phosphorus in the Western Basin, Central Basin epilimnion, and Central Basin hypolimnion of Lake Erie, 1970. Symbols denote means of observed water column data plus/minus standard deviations, lines represent model computations.

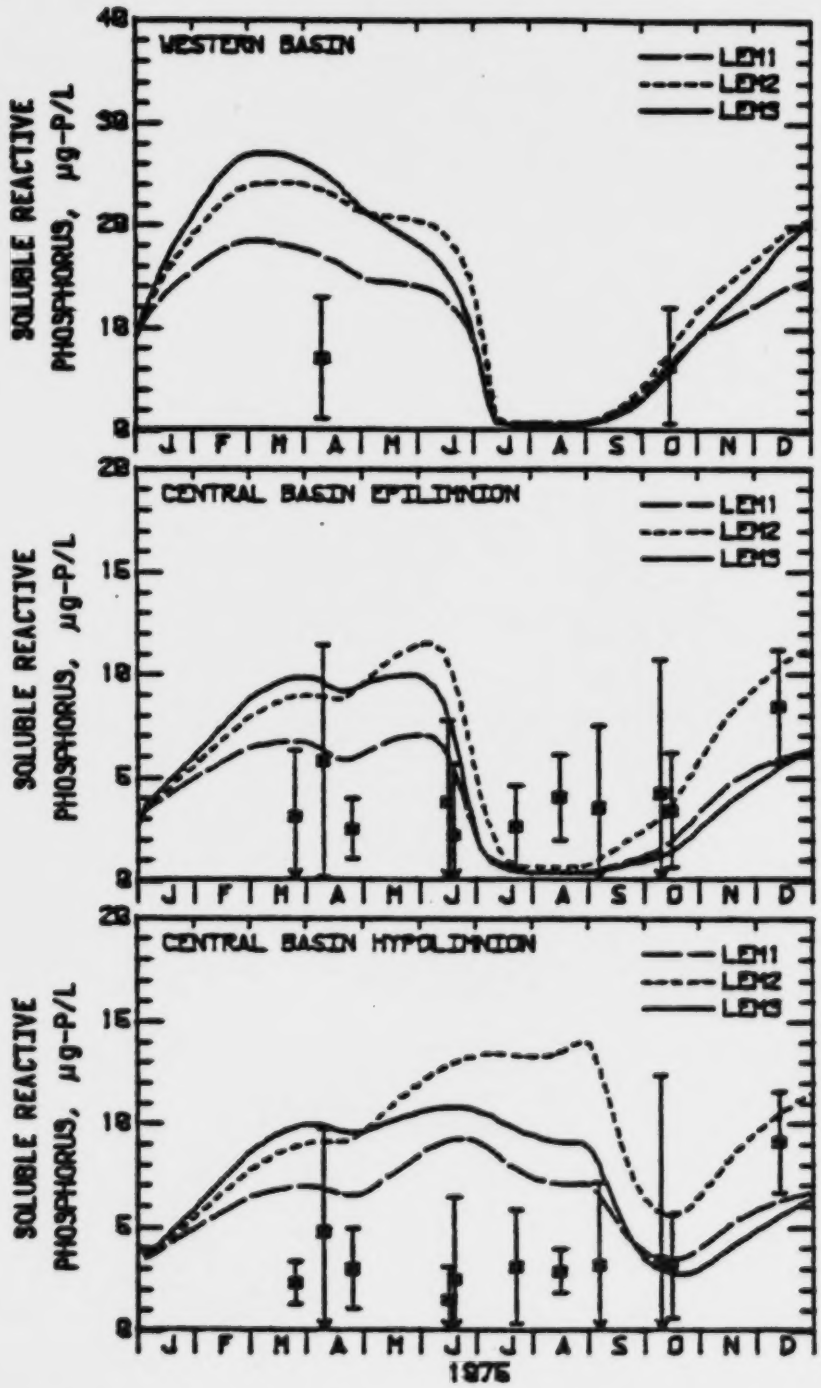

Figure 20. LEM1, LEM2, and LEM3 simulations for soluble reactive phosphorus in the Western Basin, Central Basin epilimnion, and Central Basin hypolimnion of Lake Erie, 1975.

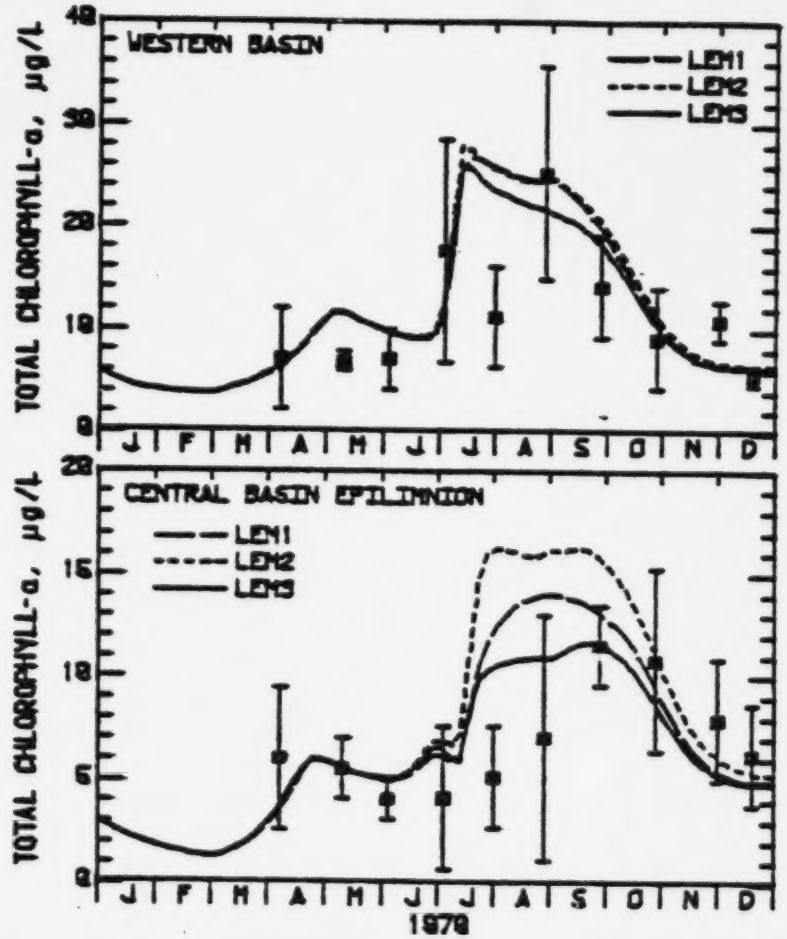

Figure 21. LEM1, LEM2, and LEM3 simulations for total chlorophyll-a in the Western Basin and Central Basin epilimnion of Lake Erie, 1970.

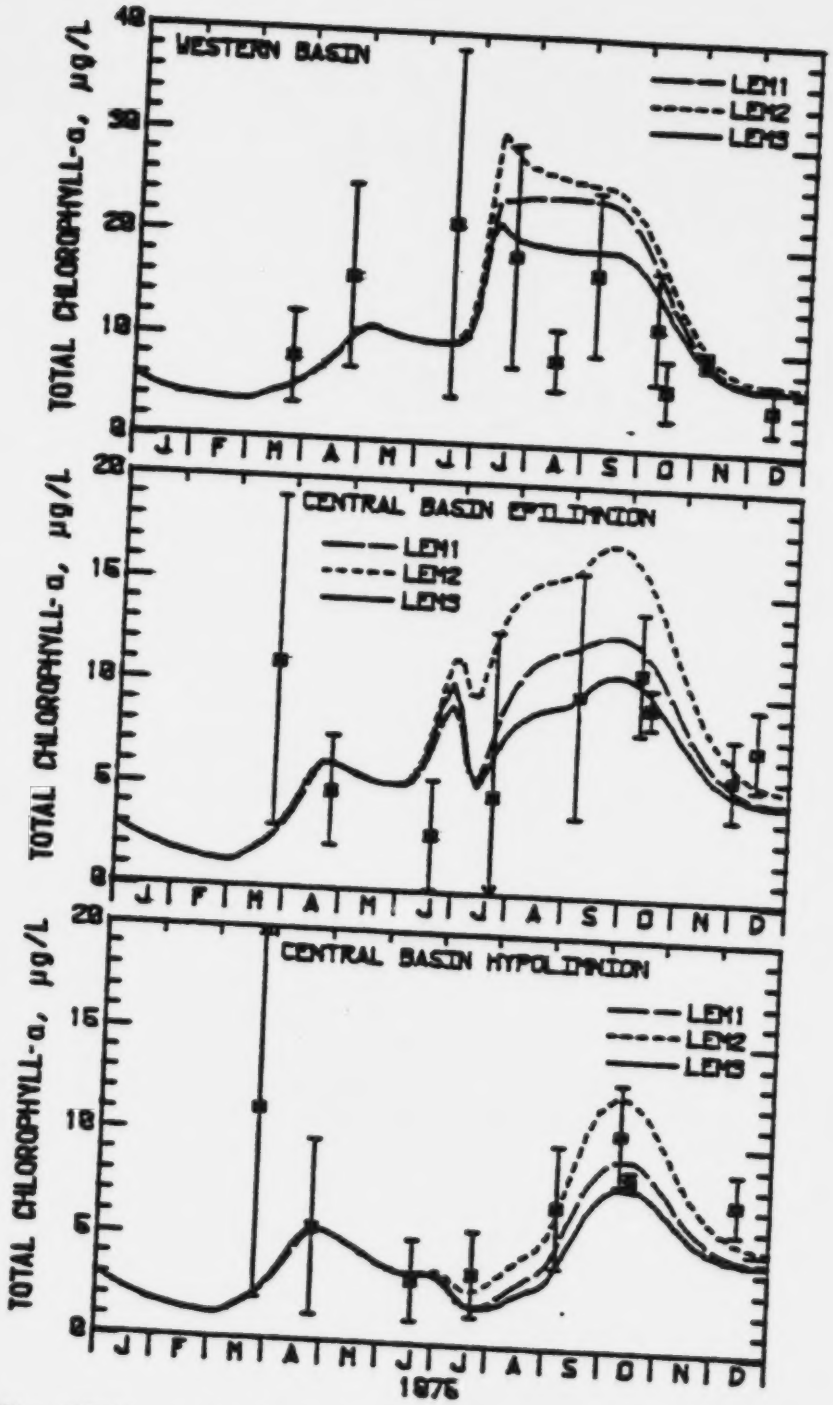

Figure 22. LEM1, LEM2, and LEM3 simulations for total chlorophyll-a in the Western Basin, Central Basin epilimnion, and Central Basin hypolimnion of Lake Erie, 1975.

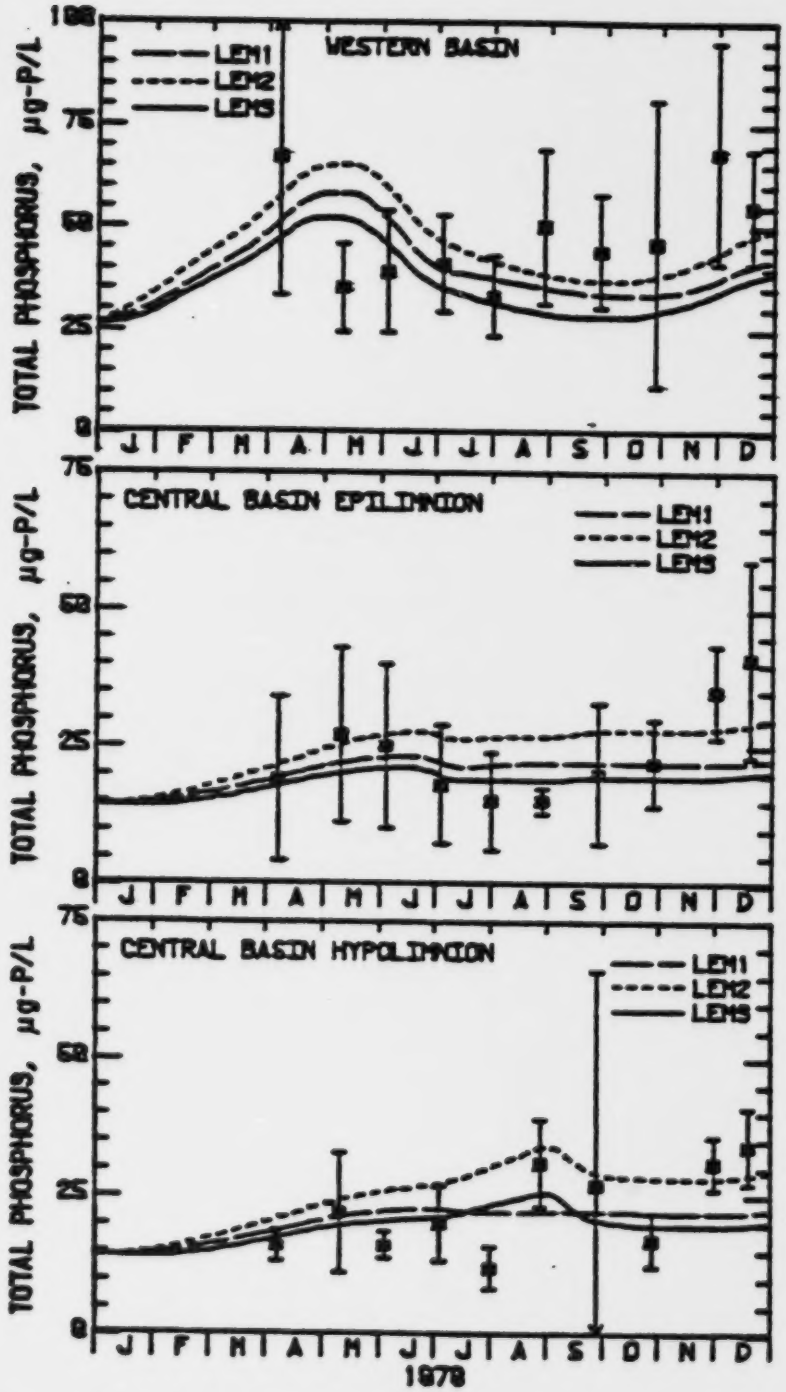

Figure 23. LEM1, LEM2, and LEM3 simulations for total phosphorus in the Western Basin, Central Basin epilimnion, and Central Basin hypolimnion of Lake Erie, 1970.

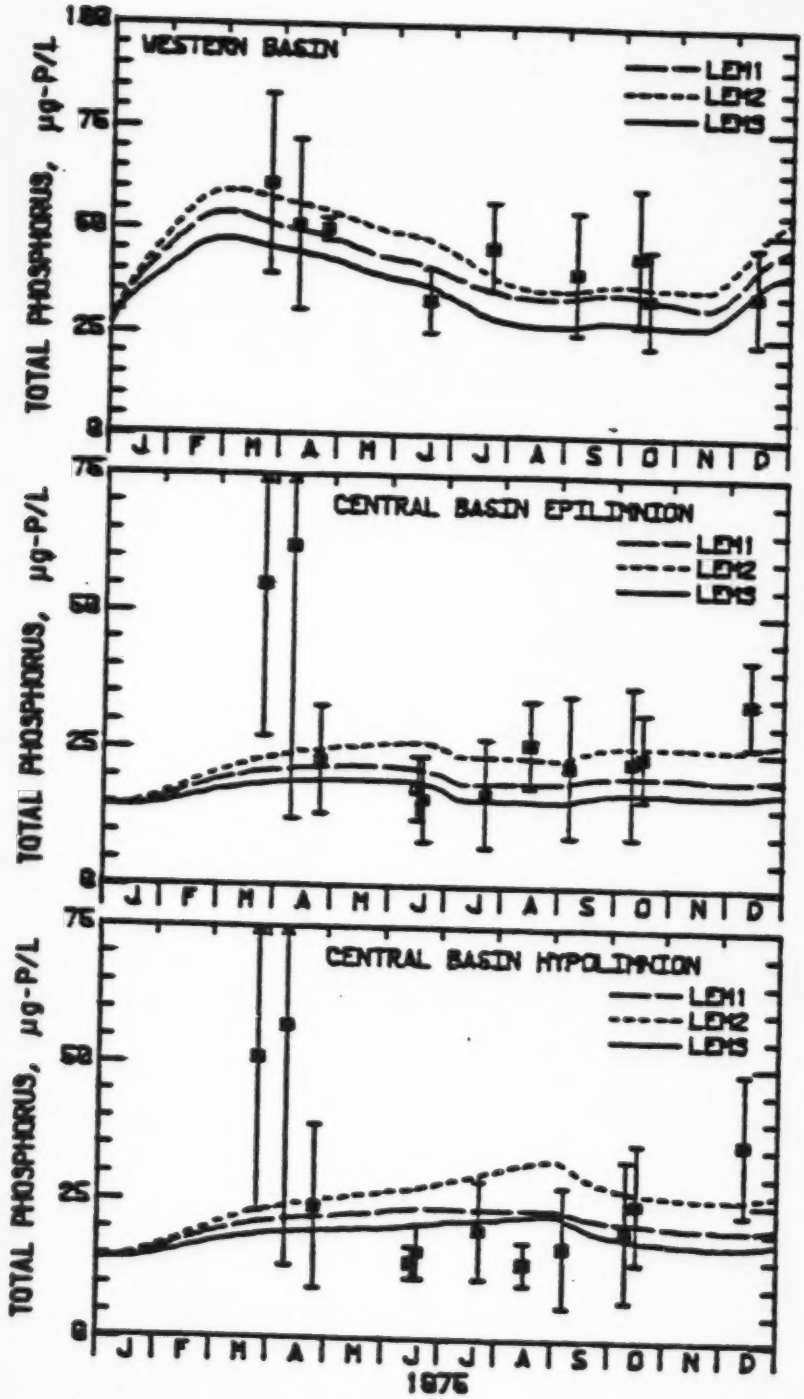

Figure 24. LEM1, LEM2, and LEM3 simulations for total phosphorus in the Western Basin, Central Basin epilimnion, and Central Basin hypolimnion of Lake Erie, 1975.

This simplistic approach is known to violate nutrient kinetics (Rodgers and Salisbury 1981b). At high SRP concentrations phytoplankton have been observed to uptake greater amounts of SRP, a phenomenon known as luxury uptake. Incorporation of a time-variable cellular P:total chlorophyll-a ratio, dependent upon in-lake SRP concentration would undoubtedly improve spring SRP simulations.

Secondly, in LEM3 the allochthonous ultimately-available P to bioavailable P (SRP) conversion rate coefficient, K_{16}, was assumed to be constant and may, as a saturating function of SRP concentration, decrease at high in-lake concentrations of SRP as LEM3 predicted for Lake Erie in the spring. The rate of SRP release from allochthonous ultimately-available particulate P (EUP) was determined in bioassays with P-starved algae in cultures with little free phosphorus (not incorporated in the algae) (DePinto et al. 1981). Utilization of P-starved algae in DCDAs provides a P sink and, thereby, maintains a low SRP concentration in the culture. Under low SRP concentration, P release is rapid (Sonzogni et al. 1982). This technique represents late-summer and fall conditions in Lake Erie when SRP concentration was low and algae were likely P-starved. However, it was not reflective of Lake Erie conditions in spring when algae were not P-starved. This limitation in LEM3 was unavoidable since measurement of the rate of SRP release from allochthonous P under a range of SRP concentrations in the experimental culture has not been undertaken.

Fall SRP simulations in the Western Basin and Central Basin epilimnion produced by LEM3 were equivalent to LEM1. Both of these models reproduced the observed data well. In contrast, LEM2 over predicted SRP data in 1970.

In the Central Basin hypolimnion the computation by LEM3 is improved compared to the LEM2 computation. However, none of the models simulated the observed SRP data except briefly during the fall overturn when SRP was transported from the hypolimnion to the epilimnion. If the observed data are accurate the models may lack a removal mechanism for SRP specific to the Central Basin hypolimnion. DiToro and Connolly (1980), noting this problem, suggested SRP adsorption to particulates and subsequent settling as a plausible removal mechanism. Alternatively, SRP overprediction in the Central Basin may have been a result of SRP overprediction in the Western Basin.

SRP was transported from the Western Basin to the Central Basin epilimnion via advection and dispersion. In the Central Basin, SRP is transported from the epilimnion to the hypolimnion via dispersion. The effect of Lake Erie hydrology on in-lake SRP concentration is apparent in Figures 19

and 20. The period of highest SRP concentration in the Central Basin hypolimnion follows that in the Central Basin epilimnion which follows that in the Western Basin. More realistic representation of SRP dynamics in the Western Basin would no doubt improve LEM3 simulations of SRP concentrations in all three segments.

Total chlorophyll-a

Total chlorophyll-a, the sum of diatom and non-diatom chlorophyll-a, simulations for 1970 are shown in Figure 21 and total chlorophyll-a simulations for 1975 are shown in Figure 22. In both 1970 and 1975 spring and early summer predictions were nearly identical by all three models. Recalling that all refinements to LEM3 occurred in the phosphorus representation, this result was to be expected since Lake Erie was not P-limited during the spring resulting in a diatom chlorophyll-a peak as shown by DiToro and Connolly (1980).

The magnitude of total chlorophyll-a concentration was predicted differently by the models in the P-limited late-summer and fall. LEM3 simulated observed total chlorophyll-a data much more closely than LEM1 and LEM2 in 1970 and 1975 in the Western Basin and Central Basin epilimnion. Significantly, LEM3 was capable of simulating total chlorophyll-a concentration more accurately than LEM1 and LEM2 without settling SRP from the water column.

Total phosphorus

Total phosphorus simulations for 1970 are shown in Figure 23 and total P simulations for 1975 are shown in Figure 24. In both 1970 and 1975, LEM3 predicted lower total P concentrations in all segments throughout most of the year than either LEM1 or LEM2, although all of the models predicted the trend and magnitude of the observed total P data. Examination of the initial and final total phosphorus concentrations illustrates that the initial and final total P concentrations computed by LEM3 varied less than in LEM1 and LEM2 in all segments in both 1970 and 1975. This greater stability indicates that LEM3 would likely simulate TP concentrations over a multi-year simulation without TP build-up in the water column.

SECTION 7

SENSITIVITY ANALYSIS

METHOD

Sensitivity analyses were performed, on the base LEM3 simulations for 1970 and 1975 (shown in Section 6), to examine the quantitative structure of the mathematical model by varying model coefficients and forcing functions. The significance of the uncertainty in these empirical parameters was realized by observing the effect, or response, on model simulations. For the analyses reported here the results were expressed as response (% change from the base model) during the phytoplankton peak in July versus the change in the parameter varied (% of the base value).

Sensitivity analyses of soluble reactive P (SRP), total P (TP), and total chlorophyll-a simulations to variations in the new P systems were examined. In order to evaluate research by DePinto et al. (1981), Kwolek (1982), and Martin (1983) and the P-bioavailability concepts utilized to define P dynamics in LEM3 only parameters related to the above research were varied from the empirical values they determined. Specifically, the bioavailable fraction of TEUP in tributary and direct non-point loads (BAPP), the EUP-to-SRP conversion rate (K), and the total external unavailable P settling velocity (SV) were varied from 25% to 200% of their base values. Sensitivity analyses of other model parameters and environmental factors have been previously analyzed (DiToro and Matystik 1980).

Varying the above parameters by 25% to 200% of the base value brackets the values measured for these parameters. The values used in the BAPP analysis are shown in Table 6. The EUP-to-SRP conversion rate was varied from 0.0385/day (nearly as slow as that rate used in LEM1 and LEM2) to 0.308/day. The TEUP settling velocity was varied from 0.1 meter/day to 0.8 meter/day, bracketing the range of the average of the median settling velocity of four Lake Erie tributaries measured by Kwolek (1982).

Since Lake Erie water quality was of greatest concern during the fall/summer phytoplankton peak, the sensitivity of LEM3 was analyzed during this period. In general, the SRP response was analyzed on the day that SRP concentration

TABLE 6. BIOAVAILABLE PP FRACTIONS OF TEUP IN TRIBUTARY AND DIRECT NON-POINT LOADS ((EUP/TEUP)X100) UTILIZED IN THE BAPP SENSITIVITY ANALYSES OF LEM3

Tributary Location	25% of base FA (percentage)	200% of base FA (percentage)
Detroit River	5.00	40.0
Western Basin	6.25	50.0
Central Basin	7.00	56.0
Eastern Basin	2.00	16.0

was most sensitive to variations in the three parameters of interest. Total chlorophyll-a response was analyzed on the day that total chlorophyll-a concentration was most sensitive to variations in the three parameters of interest. Total phosphorus was analyzed on the same day as SRP was analyzed. The total phosphorus response at that day was approximately the maximum total phosphorus response to variations in the parameters of interest.

RESULTS

The results of the sensitivity analyses are shown in Figures 25-34. The solid line represents the effect of variation of BAPP in tributary and direct non-point sources. The dashed line represents the effect of variation of K, the rate of SRP release from ultimately-available P (EUP). The dotted line represents the effect of variation in SV, the TEUP settling velocity.

In the Western Basin and Central Basin epilimnion in 1970, SRP (Figures 25-26) was extremely sensitive to variations in the bioavailability of tributary and direct non-point PP loads. The SRP response was asymetric about the base value; increasing BAPP elicited a greater SRP response than did an equivalent decrease in BAPP. In the Western Basin and Central Basin epilimnion, SRP was also quite sensitive to variations in the EUP-to-SRP conversion rate and to variations in the TEUP settling velocity. In 1975 in the Western Basin (Figure 28) LEM3 was less sensitive to increases in all three parameters compared to the Western Basin in 1970. In the Central Basin hypolimnion (Figure 27), SRP was moderately sensitive to variations in BAPP, but was

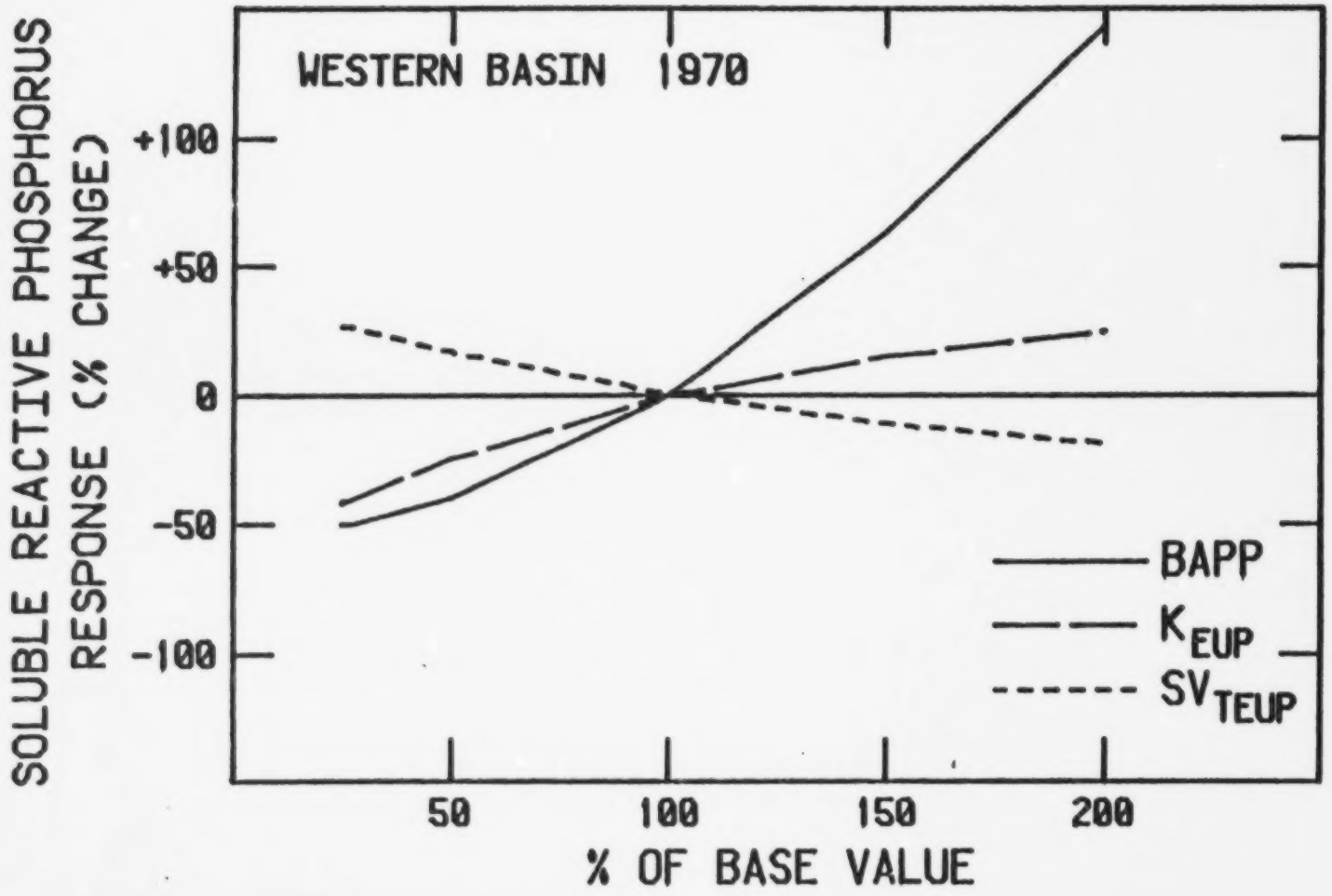

Figure 25. LEM3 soluble reactive phosphorus responses to variations in the bioavailable fraction of tributary and direct non-point loadings (BAPP), the external ultimately-available phosphorus to soluble reactive phosphorus conversion rate (K), and the total external unavailable phosphorus settling velocity (SV), in the Western Basin of Lake Erie, Julian day 195, 1970.

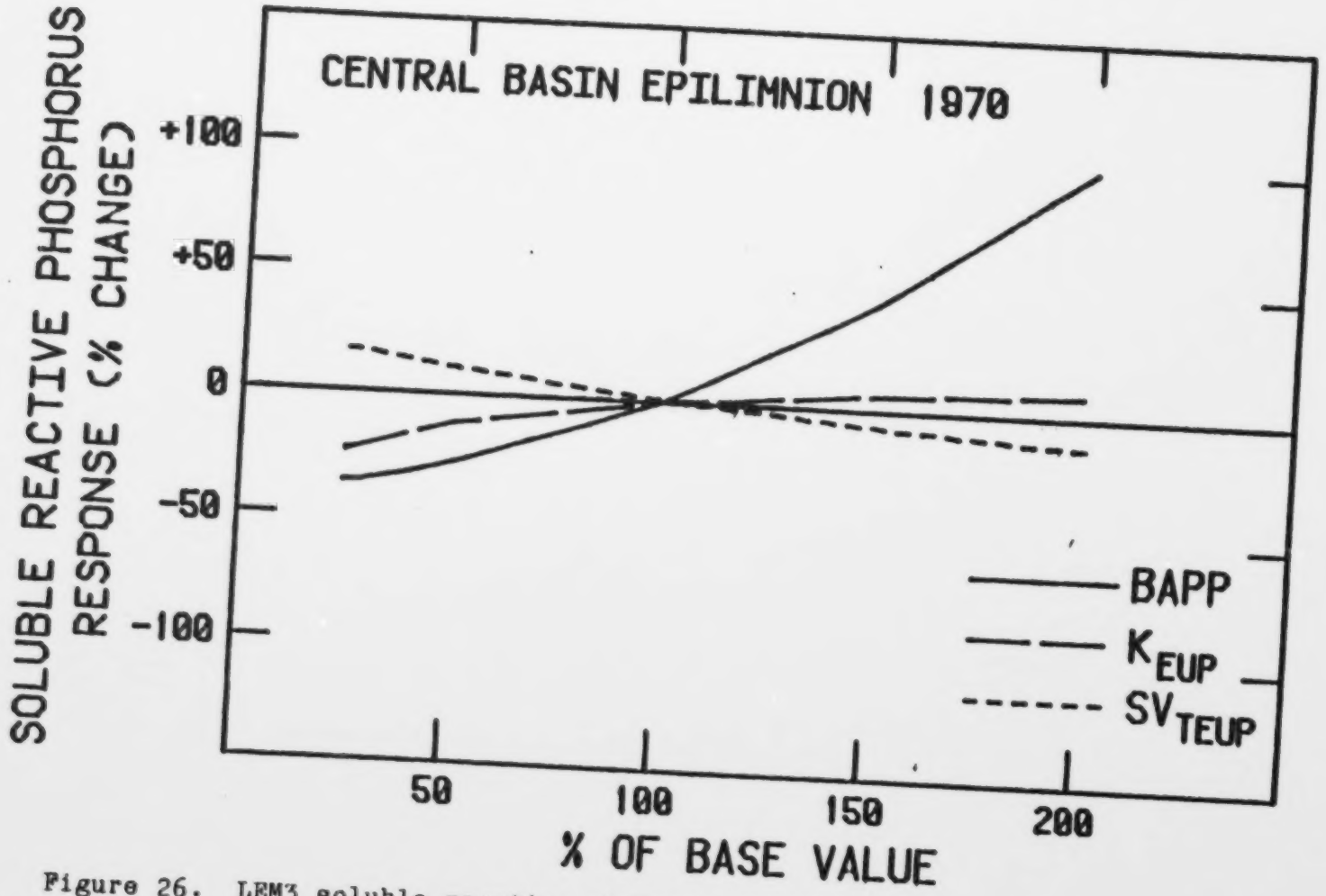

Figure 26. LEM3 soluble reactive phosphorus responses to variations in the bioavailable fraction of tributary and direct non-point loadings (BAPP), the external ultimately-available phosphorus to soluble reactive phosphorus conversion rate (K), and the total external unavailable phosphorus settling velocity (SV), in the Central Basin epilimnion of Lake Erie, Julian day 200, 1970.

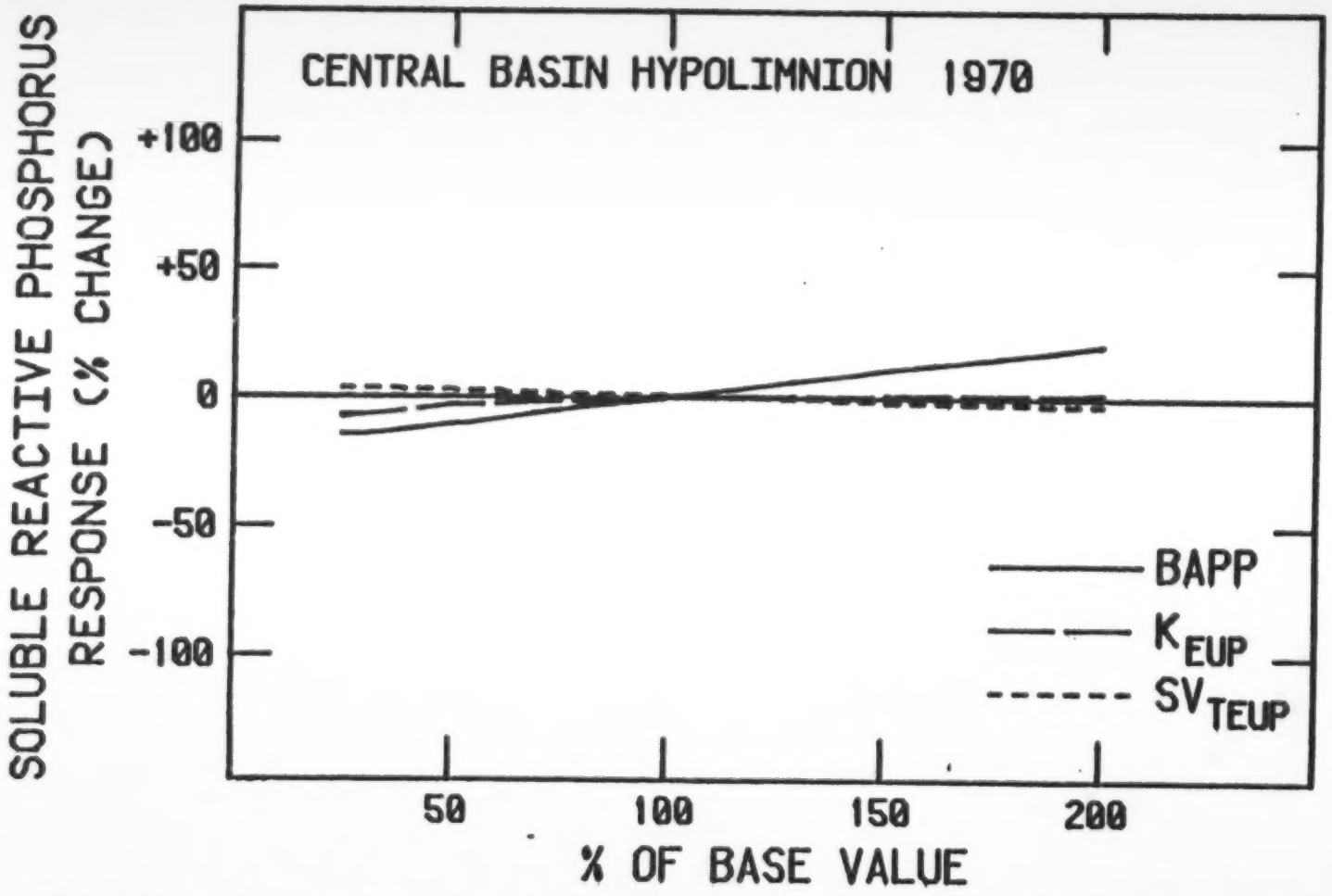

Figure 27. LEM3 soluble reactive phosphorus responses to variations in the bioavailable fraction of tributary and direct non-point loadings (BAPP), the external ultimately-available phosphorus to soluble reactive phosphorus conversion rate (K), and the total external unavailable phosphorus settling velocity (SV), in the Central Basin hypolimnion of Lake Erie, Julian day 210, 1970.

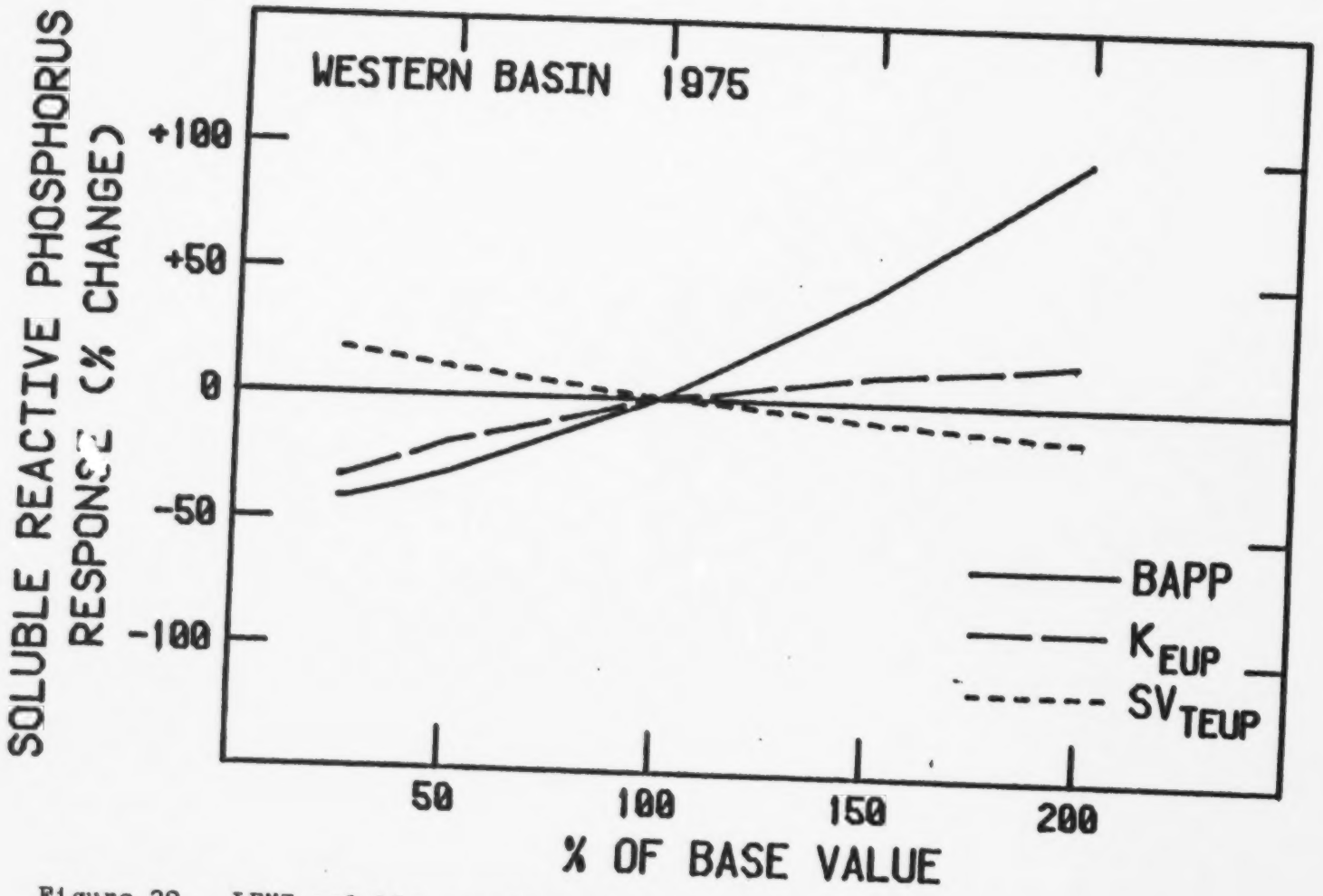

Figure 28. LEM3 soluble reactive phosphorus responses to variations in the bioavailable fraction of tributary and direct non-point loadings (BAPP), the external ultimately-available phosphorus to soluble reactive phosphorus conversion rate (K), and the total external unavailable phosphorus settling velocity (SV), in the Western Basin of Lake Erie, Julian day 190, 1975.

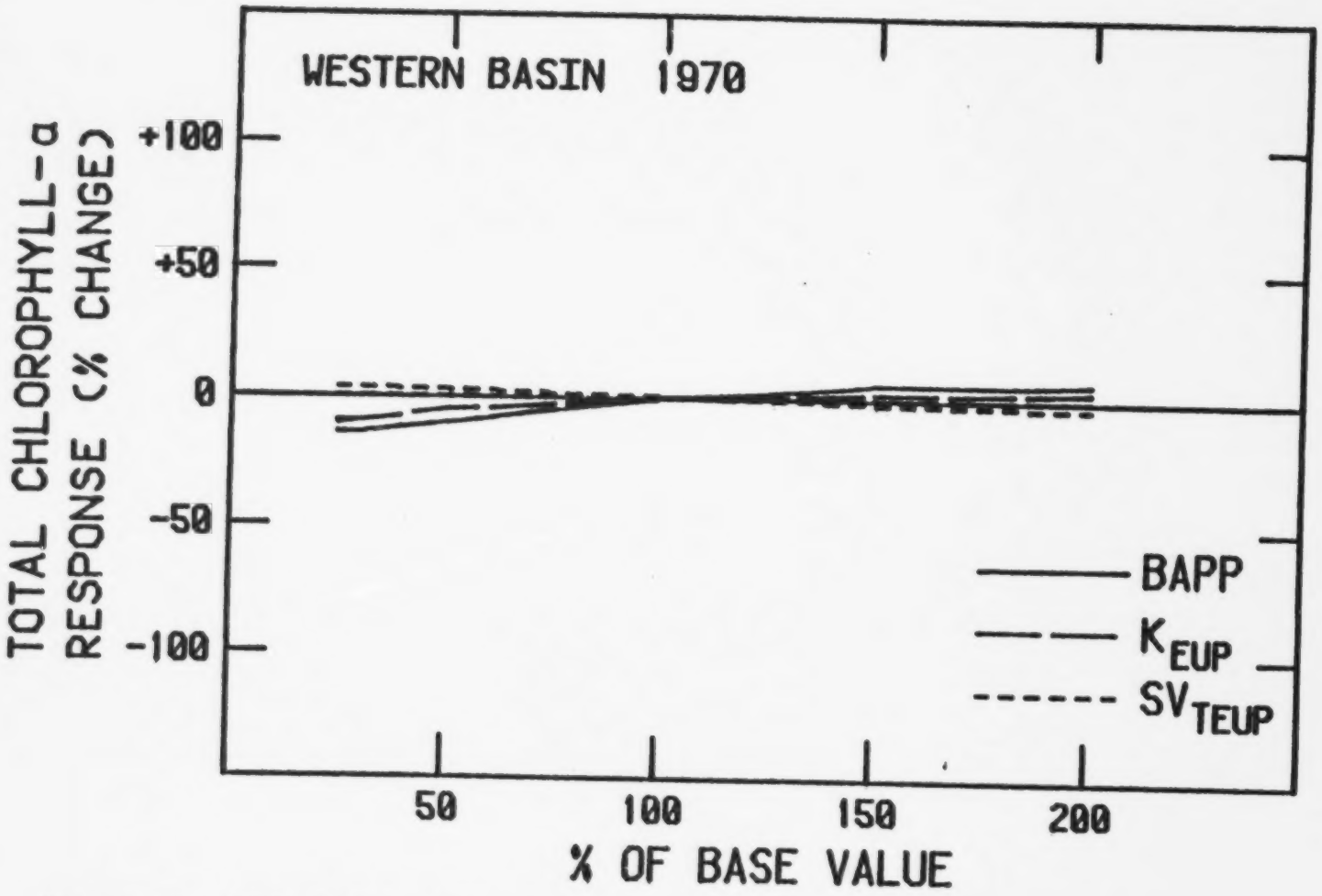

Figure 29. LEM3 total chlorophyll-a responses to variations in the bio-available fraction of tributary and direct non-point loadings (BAPP), the external ultimately-available phosphorus to soluble reactive phosphorus conversion rate (K), and the total external unavailable phosphorus settling velocity (SV), in the Western Basin of Lake Erie, Julian day 200, 1970.

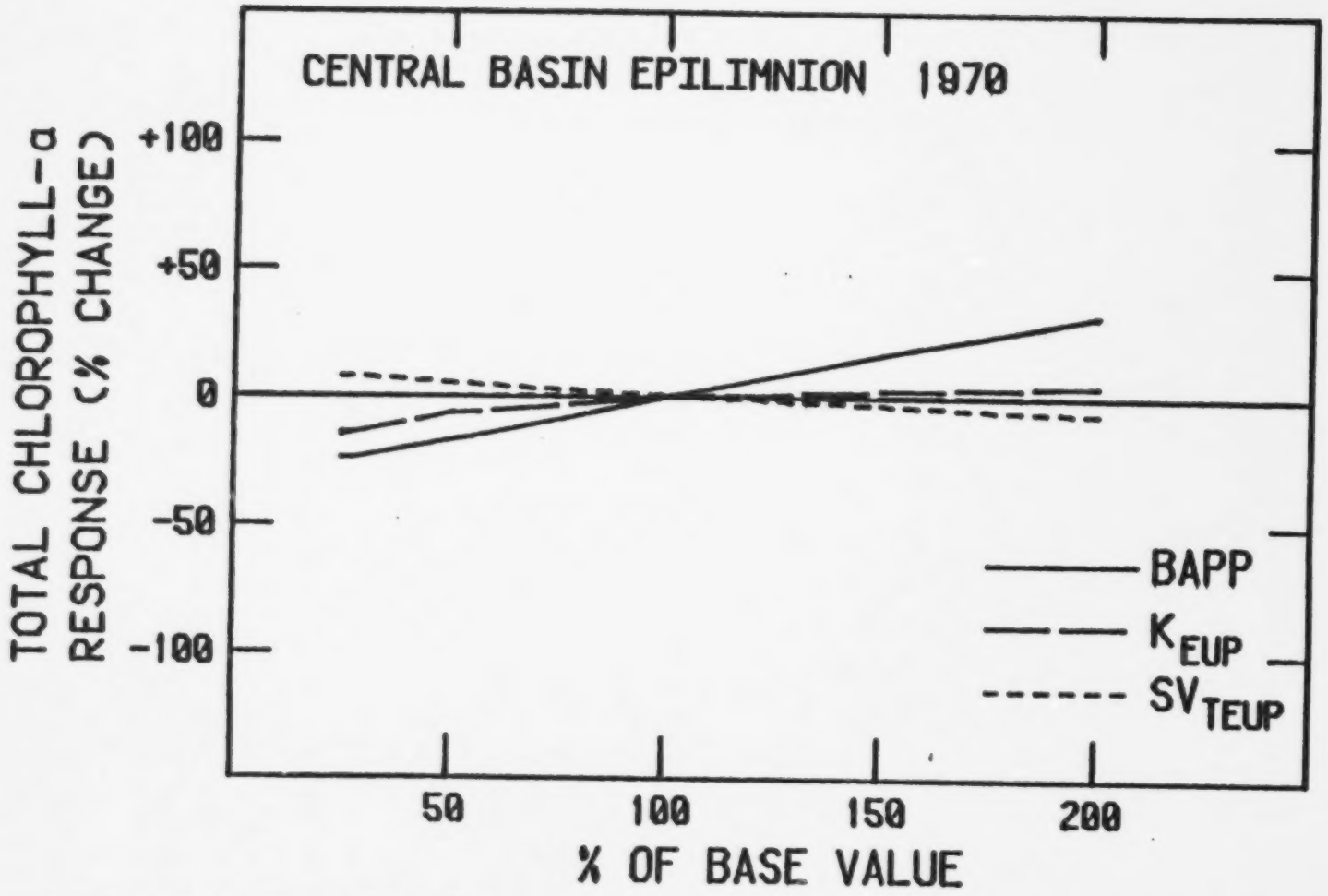

Figure 30. LEM3 total chlorophyll-a responses to variations in the bio-available fraction of tributary and direct non-point loadings (BAPP), the external ultimately-available phosphorus to soluble reactive phosphorus conversion rate (K), and the total external unavailable phosphorus settling velocity (SV), in the Central Basin epilimnion of Lake Erie, Julian day 205, 1970.

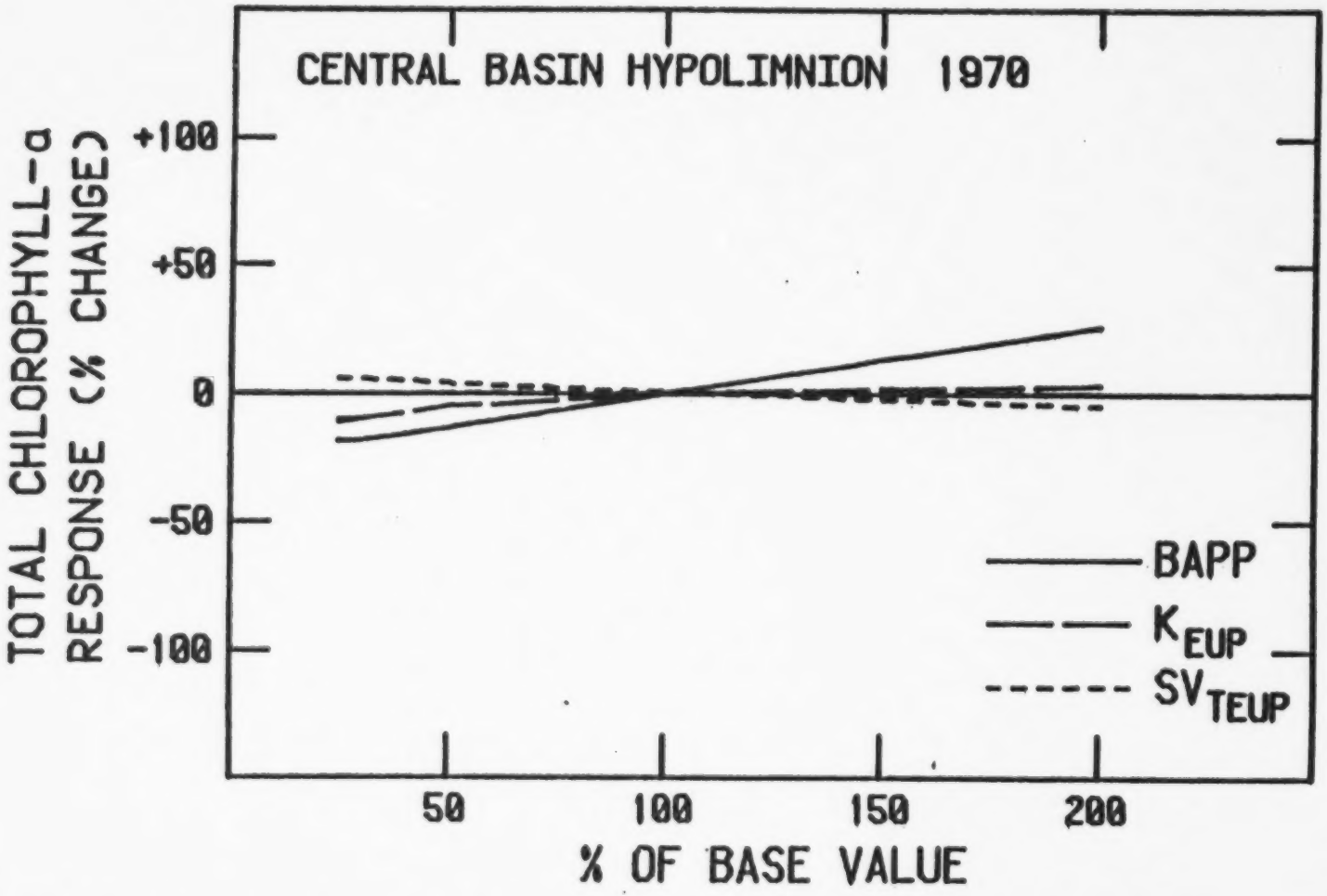

Figure 31. LEM3 total chlorophyll-a responses to variations in the bio-available fraction of tributary and direct non-point loadings (BAPP), the external ultimately-available phosphorus to soluble reactive phosphorus conversion rate (K), and the total external unavailable phosphorus settling velocity (SV), in the Central Basin hypolimnion of Lake Erie, Julian day 215, 1970.

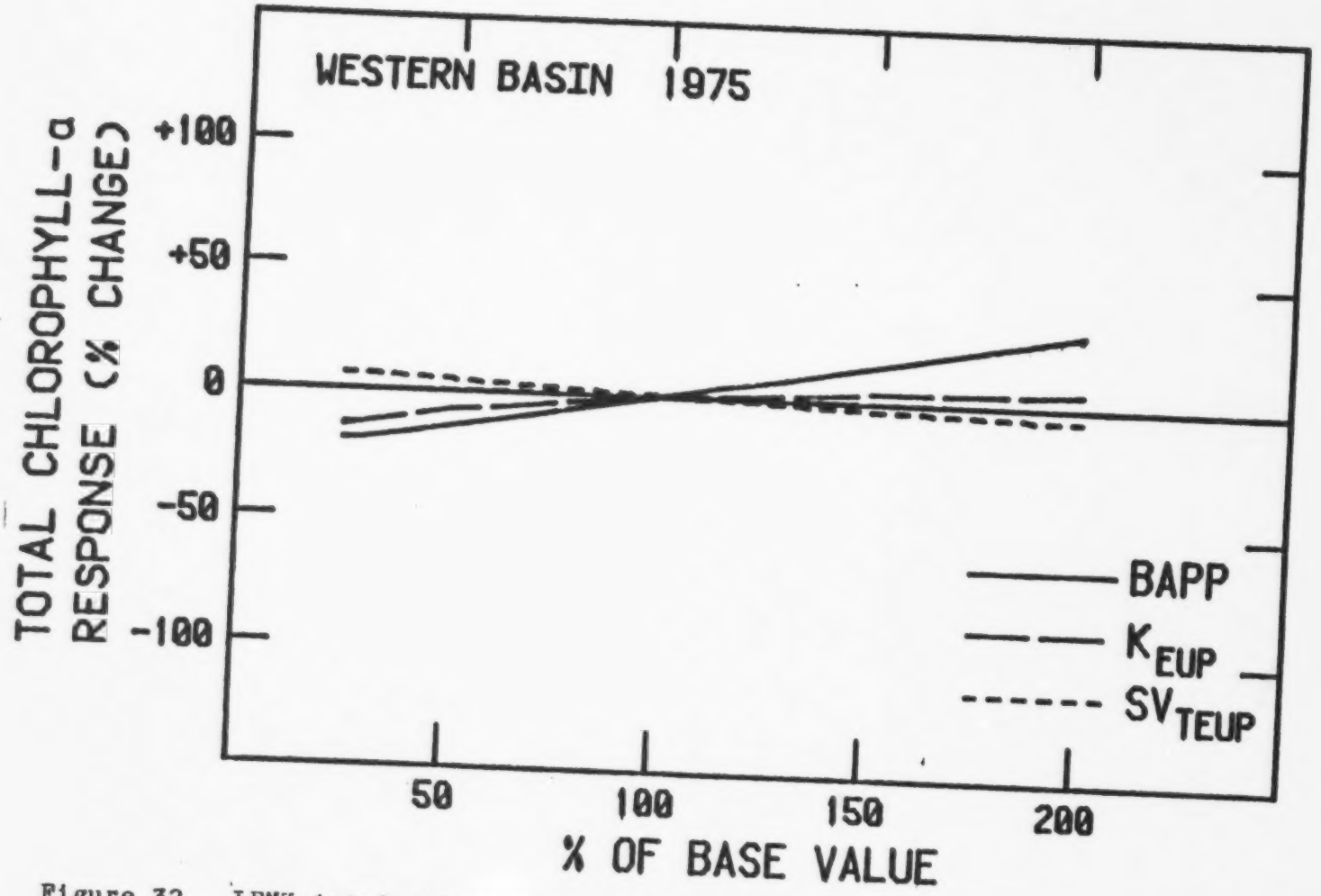

Figure 32. LEM3 total chlorophyll-a responses to variations in the bio-available fraction of tributary and direct non-point loadings (BAPP), the external ultimately-available phosphorus to soluble reactive phosphorus conversion rate (K), and the total external unavailable phosphorus settling velocity (SV), in the Western Basin of Lake Erie, Julian day 195, 1975.

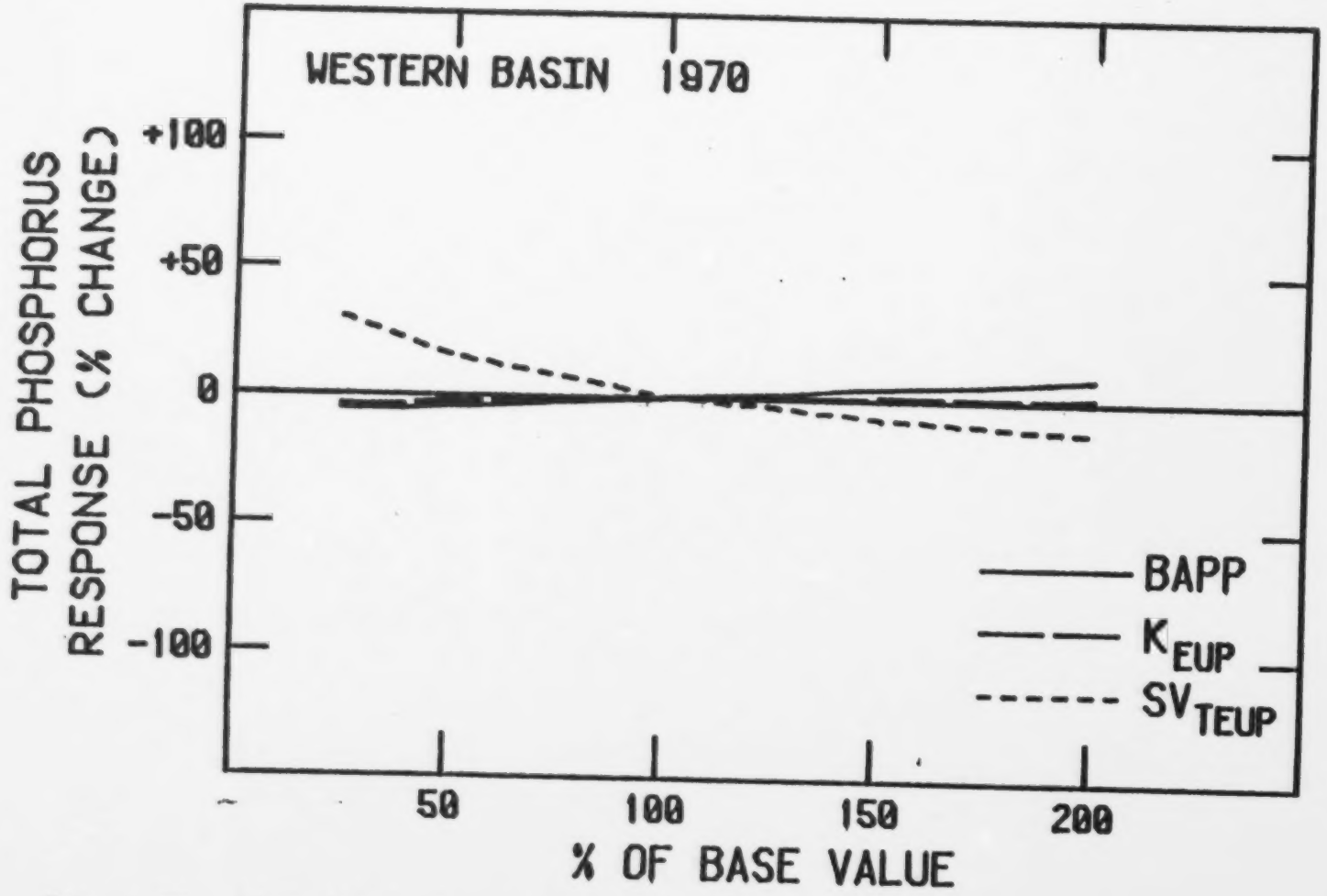

Figure 33. LEM3 total phosphorus responses to variations in the bioavailable fraction of tributary and direct non-point loadings (BAPP), the external ultimately-available phosphorus to soluble reactive phosphorus conversion rate (K), and the total external unavailable phosphorus settling velocity (SV), in the Western Basin of Lake Erie, Julian day 195, 1970.

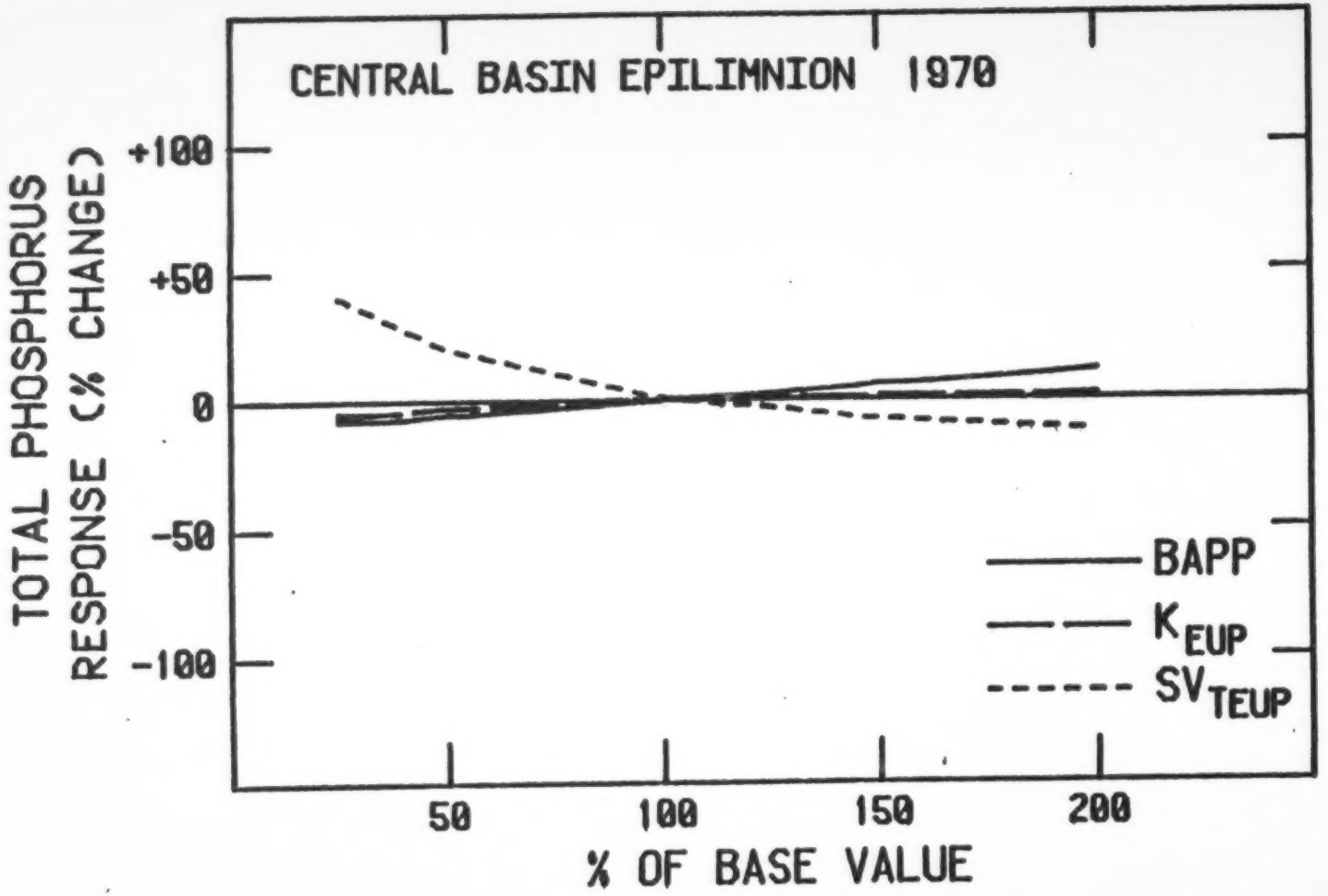

Figure 34. LEM3 total phosphorus responses to variations in the bioavailable fraction of tributary and direct non-point loadings (BAPP), the external ultimately-available phosphorus to soluble reactive phosphorus conversion rate (K), and the total external unavailable phosphorus settling velocity (SV), in the Central Basin epilimnion of Lake Erie, Julian day 200, 1970.

relatively insensitive to variations in the EUP-to-SRP conversion rate and to variations in the TEUP settling velocity.

Total chlorophyll-a (Figures 29-32) was especially sensitive to variations in the bioavailability of tributary and direct non-point PP loads, moderately sensitive to variations in the EUP-to-SRP conversion rate, and relatively insensitive to variations in the TEUP settling velocity. The Western Basin was less sensitve in 1970 than in 1975 to variation in all three parameters.

TP (Figures 33 and 34) was especially sensitive to variations in the TEUP settling velocity. The shallow Western Basin was less sensitive than the Central Basin to decreases in the TEUP settling velocity. This result was to be expected; particle concentration will be affected less by changes in the settling velocity of the particle in a shallow water column compared to a deep water column since there is less vertical distance for the effect to take place. In contrast, TP was relatively insensitive to variations in EUP-to-SRP conversion rate and to variations in the bioavailability of tributary and direct non-point PP loads.

Insight into LEM3 dynamics was gained from the sensitivity analysis curves by examining the trends on the SRP, TP, and total chlorophyll-a concentrations caused by changing the model parameters. Increasing the bioavailability of tributary and direct non-point PP loads increased the EUP loading allowing more P to be internally recycled resulting in higher SRP, TP, and total chlorophyll-a concentrations in the water column. Increasing the EUP-to-SRP conversion rate increased the proportion of P in a dissolved form (SRP), which does not settle from the water column, allowing more P to be internally recycled resulting in higher SRP, TP, and total chlorophyll-a concentrations in the water column. Increasing the settling velocity of TEUP removed EUP from the water column faster decreasing the concentration of ultimately-available P available for internal recycle resulting in a decrease in SRP, TP, and total chlorophyll-a concentrations in the water column.

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TABLE A-1. Monthly soluble reactive (SRP), external ultimately-available (EUP), and external refractory (ERP), phospnorus loadings (Metric tons) to Lake Erie by basin from 1970 to 1980

	WESTERN BASIN			CENTRAL BASIN			EASTERN BASIN		
	SRP	EUP	ERP	SRP	EUP	ERP	SRP	EUP	ERP
1970 JAN	433.8	106.7	363.2	134.8	95.5	186.1	27.3	4.0	42.4
1970 FEB	470.7	156.2	514.2	145.6	106.3	219.2	28.5	5.5	59.8
1970 MAR	593.1	216.6	722.3	168.5	130.0	274.9	37.1	9.1	100.1
1970 APR	664.1	300.9	1003.5	162.3	120.4	252.5	63.2	23.0	260.0
1970 MAY	539.6	300.0	953.5	127.3	77.0	138.5	36.1	6.8	74.3
1970 JUN	439.3	133.4	445.5	121.5	66.6	113.9	27.6	3.5	36.4
1970 JUL	454.6	136.9	457.8	108.6	58.5	91.0	30.3	4.0	41.7
1970 AUG	433.4	115.4	391.8	104.5	53.0	76.9	30.1	4.8	51.6
1970 SEP	415.2	101.0	347.0	103.1	55.5	85.4	29.2	5.2	55.2
1970 OCT	438.0	106.9	366.7	114.5	67.8	114.9	30.0	5.7	61.3
1970 NOV	444.1	126.8	432.9	132.8	90.8	176.1	39.6	10.0	111.1
1970 DEC	508.8	179.4	605.1	151.1	93.3	180.7	47.6	11.0	122.4
1971 JAN	426.8	115.0	405.1	112.0	58.8	103.0	31.1	4.5	47.8
1971 FEB	580.3	291.6	953.5	196.3	219.9	521.3	29.6	8.6	95.5
1971 MAR	602.2	498.0	1872.8	175.1	110.1	234.6	46.1	13.7	153.0
1971 APR	463.1	147.8	534.4	106.1	57.8	102.1	69.3	31.7	360.0
1971 MAY	472.8	194.1	638.7	119.2	68.8	128.6	28.6	4.5	47.8
1971 JUN	426.1	142.7	481.4	97.1	50.5	83.4	25.8	3.7	38.6
1971 JUL	414.0	111.7	390.0	95.0	46.3	70.7	25.9	3.1	31.5
1971 AUG	408.1	108.3	380.3	92.8	44.6	66.4	25.6	3.2	32.8
1971 SEP	397.0	106.5	372.7	92.7	45.3	69.8	23.3	2.9	28.9
1971 OCT	412.4	109.6	383.4	95.5	46.6	71.3	24.0	2.9	29.0
1971 NOV	397.9	106.1	371.6	94.5	49.5	80.5	21.7	2.9	29.7
1971 DEC	476.2	169.9	572.2	127.3	92.5	189.5	29.2	8.3	91.1
1972 JAN	512.6	138.5	475.8	112.4	62.5	118.5	23.9	4.8	51.2
1972 FEB	428.7	104.7	362.8	96.9	53.1	96.4	21.2	3.1	32.8
1972 MAR	643.4	255.5	879.7	201.2	182.6	427.0	44.5	20.4	230.2
1972 APR	724.4	381.9	1261.8	165.2	134.9	305.9	80.0	50.5	577.9
1972 MAY	513.9	147.3	501.9	117.2	73.7	147.3	28.5	6.3	67.8
1972 JUN	454.4	129.1	438.2	105.8	104.8	228.3	49.0	14.1	158.3
1972 JUL	489.8	149.9	504.0	103.9	57.8	106.2	25.2	4.1	42.6
1972 AUG	463.6	116.5	404.1	95.2	45.4	74.4	22.0	3.2	32.1
1972 SEP	521.9	265.2	846.3	110.9	64.3	124.3	19.6	2.8	28.9
1972 OCT	513.8	172.8	575.1	108.0	62.4	118.2	25.3	4.3	45.5
1972 NOV	702.7	601.5	1872.4	173.4	132.4	299.3	30.3	6.9	75.8
1972 DEC	653.9	365.1	1178.7	175.7	124.5	277.7	32.8	10.3	114.5
1973 JAN	656.2	228.3	818.3	100.1	68.2	138.0	39.1	9.5	105.5
1973 FEB	500.8	138.8	493.6	93.3	58.8	117.1	29.8	6.4	70.6
1973 MAR	932.1	544.8	1860.1	216.7	199.9	476.4	79.2	41.4	472.5
1973 APR	600.9	181.3	636.9	123.8	94.1	205.8	41.9	13.1	146.4
1973 MAY	561.4	204.0	696.7	120.1	83.8	178.0	34.9	7.7	84.4
1973 JUN	600.3	304.4	991.0	111.6	83.2	177.7	23.3	4.6	48.9
1973 JUL	536.1	174.4	596.2	79.8	45.9	80.6	20.9	3.0	30.0
1973 AUG	495.6	123.5	444.4	71.0	40.1	65.6	21.7	2.8	28.3
1973 SEP	459.8	109.3	398.9	64.9	33.4	49.7	19.2	2.5	24.2
1973 OCT	472.7	112.1	407.9	71.1	38.5	61.4	20.7	2.6	26.3
1973 NOV	498.9	129.9	473.4	92.3	57.2	110.8	29.4	6.4	69.3
1973 DEC	611.0	332.3	1097.8	116.2	84.9	180.9	31.5	7.8	86.0

(continued)

TABLE A-1. Continued

	WESTERN BASIN			CENTRAL BASIN			EASTERN BASIN		
	SRP	EUP	ERP	SRP	EUP	ERP	SRP	EUP	ERP
1974 JAN	662.8	503.1	1659.4	172.5	163.3	388.1	39.6	11.3	126.1
1974 FEB	483.9	238.6	812.2	92.9	67.4	144.4	31.5	7.6	84.4
1974 MAR	655.2	392.0	1339.3	163.2	156.4	370.4	60.1	30.9	351.1
1974 APR	516.8	250.0	862.5	120.8	113.1	260.3	53.6	26.1	295.9
1974 MAY	513.6	253.1	884.3	102.7	85.0	186.7	57.8	35.5	403.9
1974 JUN	366.2	119.7	432.3	70.3	37.8	66.4	23.4	4.0	42.0
1974 JUL	353.0	111.5	408.6	64.4	42.4	77.4	20.8	3.7	38.2
1974 AUG	348.5	108.7	398.7	64.4	36.3	61.6	19.1	2.5	24.1
1974 SEP	332.8	104.3	382.2	59.7	33.3	54.9	18.0	2.5	24.5
1974 OCT	344.9	105.7	387.8	61.8	32.4	51.4	20.2	2.7	27.2
1974 NOV	347.7	107.3	392.6	94.0	78.2	170.4	22.4	5.5	59.0
1974 DEC	401.2	168.7	580.4	136.7	106.5	242.0	21.3	4.2	44.6
1975 JAN	516.3	229.6	785.5	143.6	127.4	302.5	24.5	8.8	96.8
1975 FEB	545.2	274.1	919.8	145.2	162.2	394.1	25.5	10.9	121.5
1975 MAR	535.9	213.7	773.0	149.0	112.2	263.4	48.6	19.1	215.5
1975 APR	500.2	193.4	704.9	74.6	43.6	97.2	59.1	31.7	360.4
1975 MAY	432.6	184.3	614.1	85.8	49.7	101.6	24.8	4.8	50.3
1975 JUN	416.9	179.0	600.4	86.8	61.4	133.2	21.5	7.7	84.3
1975 JUL	357.2	124.7	432.6	56.6	30.2	52.3	17.8	2.4	25.5
1975 AUG	368.5	121.8	428.4	71.1	41.1	80.4	23.8	4.4	47.0
1975 SEP	397.2	138.4	487.6	96.8	62.1	134.8	20.8	3.6	37.5
1975 OCT	357.9	122.4	425.6	68.0	36.2	67.7	18.5	3.1	31.4
1975 NOV	347.7	99.8	357.5	63.6	34.1	62.8	20.8	3.9	40.9
1975 DEC	476.8	257.4	848.6	103.3	79.3	178.8	35.6	9.1	100.1
1976 JAN	348.5	121.0	430.3	202.0	113.7	271.7	24.5	9.4	103.4
1976 FEB	781.3	704.4	2307.6	338.4	210.3	521.6	66.7	29.0	329.9
1976 MAR	615.3	422.1	1489.3	138.5	120.9	290.1	93.2	62.3	712.8
1976 APR	349.3	127.7	473.6	73.1	42.0	87.5	42.2	14.7	164.3
1976 MAY	367.1	131.4	488.6	64.3	31.9	61.2	38.7	10.6	117.9
1976 JUN	285.3	89.9	329.7	51.8	25.9	46.1	18.6	3.4	34.8
1976 JUL	309.0	106.7	398.1	65.7	41.6	86.1	22.1	5.7	60.9
1976 AUG	281.6	94.2	350.1	52.6	26.6	47.5	20.3	4.0	41.9
1976 SEP	262.3	83.8	310.6	52.6	31.8	61.4	21.1	3.3	33.5
1976 OCT	273.5	88.0	325.9	53.8	29.2	54.5	21.5	6.0	64.6
1976 NOV	262.8	89.0	331.4	53.8	28.0	51.6	23.7	5.2	55.0
1976 DEC	258.3	87.4	322.3	55.8	35.1	69.5	20.7	4.4	45.9
1977 JAN	218.9	68.6	234.9	69.4	25.3	34.7	17.8	2.5	24.7
1977 FEB	230.5	73.8	251.6	120.9	105.2	242.8	16.3	4.3	44.7
1977 MAR	602.4	452.1	1611.1	198.1	138.6	326.0	71.4	48.9	557.7
1977 APR	432.4	303.5	980.5	123.8	76.5	167.0	39.3	16.7	187.7
1977 MAY	295.6	112.0	370.9	89.6	36.3	62.9	17.5	4.2	44.3
1977 JUN	231.9	69.7	239.0	71.4	26.7	38.8	17.3	2.5	24.7
1977 JUL	251.8	80.8	275.0	88.4	50.8	100.2	18.6	4.0	41.7
1977 AUG	242.9	75.2	256.9	83.1	37.2	65.4	20.6	4.4	46.3
1977 SEP	283.1	103.7	354.7	93.6	48.7	95.3	34.0	26.2	296.9
1977 OCT	277.5	94.1	333.4	89.5	34.2	57.5	44.2	12.4	138.1
1977 NOV	276.9	91.4	322.5	96.7	48.7	95.3	35.7	10.0	111.4
1977 DEC	584.0	758.0	2390.1	284.7	300.4	742.2	46.4	22.0	249.4

(continued)

TABLE A-1. Continued

	WESTERN BASIN			CENTRAL BASIN			EASTERN BASIN		
	SRP	EUP	ERP	SRP	EUP	ERP	SRP	EUP	ERP
1978 JAN	254.4	69.5	239.9	165.5	105.8	234.0	23.4	3.6	37.5
1978 FEB	211.0	58.7	203.5	121.3	52.0	99.1	17.0	2.2	21.4
1978 MAR	676.1	339.7	1083.9	338.3	416.9	1033.9	32.2	9.9	110.3
1978 APR	579.9	239.5	786.3	208.5	117.0	263.8	77.1	22.4	254.1
1978 MAY	315.4	82.2	281.0	152.4	68.2	137.4	29.4	3.7	39.7
1978 JUN	253.6	72.9	248.7	115.6	44.4	77.2	15.0	2.2	21.7
1978 JUL	265.9	72.8	249.0	112.2	43.8	74.4	15.1	2.5	25.1
1978 AUG	231.0	63.8	221.8	108.5	42.5	71.2	14.6	2.6	26.1
1978 SEP	227.6	61.9	216.0	101.3	39.8	65.5	16.1	2.5	25.7
1978 OCT	239.3	64.3	224.7	111.9	43.6	74.1	16.2	2.6	25.9
1978 NOV	232.2	62.8	218.8	103.9	41.5	69.3	18.1	2.3	22.5
1978 DEC	255.7	69.6	241.4	129.3	53.9	100.6	20.5	3.2	33.8
1979 JAN	264.1	52.0	179.8	106.1	74.1	160.5	24.5	10.3	114.1
1979 FEB	224.1	42.3	144.7	107.1	83.3	187.3	15.0	2.7	27.5
1979 MAR	523.1	167.5	554.5	218.0	245.9	602.4	64.6	27.0	306.5
1979 APR	538.6	170.2	570.8	205.7	169.2	405.6	64.7	13.8	155.1
1979 MAY	316.2	74.7	251.3	109.4	95.2	215.1	25.8	3.2	32.2
1979 JUN	251.0	48.3	168.2	82.7	34.8	60.1	16.1	2.1	20.4
1979 JUL	282.9	56.0	192.0	78.1	32.1	52.7	14.2	2.4	24.0
1979 AUG	305.3	63.6	214.7	92.5	40.9	75.4	14.7	2.5	24.5
1979 SEP	234.3	45.3	158.3	92.1	78.1	171.6	15.3	11.2	124.5
1979 OCT	235.2	43.6	154.5	82.9	41.4	76.6	15.4	3.1	31.1
1979 NOV	299.3	74.5	252.4	128.3	72.0	155.8	22.1	3.1	32.0
1979 DEC	415.0	131.7	435.7	166.4	145.9	345.4	38.7	9.8	109.0
1980 JAN	320.8	60.5	210.2	97.1	49.8	99.0	27.3	4.2	44.6
1980 FEB	252.7	47.2	164.0	75.6	51.4	105.0	13.0	2.3	22.6
1980 MAR	517.9	198.9	646.7	185.1	236.7	579.5	40.4	13.2	148.2
1980 APR	452.7	133.0	446.0	146.4	134.4	317.2	37.8	6.6	72.1
1980 MAY	311.4	60.1	206.9	77.0	35.1	61.0	23.2	2.7	27.1
1980 JUN	350.7	104.0	336.7	84.4	59.8	125.6	16.0	2.3	22.5
1980 JUL	285.9	55.4	191.0	70.1	36.2	63.9	16.4	2.6	26.1
1980 AUG	301.2	59.9	204.5	81.6	49.1	97.0	16.1	2.6	26.3
1980 SEP	251.2	46.1	161.6	63.5	29.8	48.4	14.3	2.2	21.6
1980 OCT	244.0	43.3	154.5	62.9	33.6	57.2	18.1	6.3	68.5
1980 NOV	231.4	41.4	147.3	58.5	26.5	39.8	16.9	2.0	19.1
1980 DEC	283.5	52.9	185.5	73.8	37.6	67.4	23.7	3.4	35.4